

NASA Technical Memorandum 80045

METEOROLOGICAL AND OPERATIONAL ASPECTS
OF 46 CLEAR AIR TURBULENCE SAMPLING MISSIONS
WITH AN INSTRUMENTED B-57B AIRCRAFT

VOLUME II (APPENDIX C) - TURBULENCE
MISSIONS

(NASA-TM-80045) METEOROLOGICAL AND
OPERATIONAL ASPECTS OF 46 CLEAR AIR *HC A09/MFAS1* N79-27772
TURBULENT SAMPLING MISSIONS WITH AN
INSTRUMENTED B-57B AIRCRAFT. VOLUME 2,
APPENDIX C: TURBULENCE MISSIONS (NASA) G3/47 Unclass 29324

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APPENDIX C

CONTENTS

	Page
SUMMARY	1
TABLE C-1. - MAT B-57B Missions Covered by Narrative Summaries	3
SUMMARIES:	
Flight 8 (June 19, 1974)	4
Flight 9 (June 20, 1974)	6
Flight 14 (November 7, 1974)	8
Flight 15 (November 8, 1974)	16
Flight 18 (November 21, 1974)	20
Flight 19 (November 26, 1974)	22
Flight 20 (December 3, 1974)	28
Flight 24 (December 17, 1974)	38
Flight 25 (December 31, 1974)	48
Flight 26 (January 14, 1975)	50
Flight 27 (January 30, 1975)	61
Flight 28 (February 14, 1975)	69
Flight 29 (February 20, 1975)	78
Flight 30 (March 7, 1975)	87
Flight 31 (March 25, 1975)	101
Flight 32 (March 26, 1975)	104
Flight 33 (March 28, 1975)	121
Flight 34 (April 4, 1975)	123
Flight 35 (April 5, 1975)	134

CONTENTS

	Page
Flight 36 (April 14, 1975)	136
Flight 37 (April 17, 1975)	138
Flight 38 (April 24, 1975)	140
Flight 39 (May 20, 1975)	146
Flight 40 (May 20, 1975)	159
Flight 41 (May 21, 1975)	162
Flight 42 (June 13, 1975)	175
Flight 43 (June 17, 1975)	182

SUMMARY

The results of 46 clear air turbulence (CAT) probing missions conducted with an extensively instrumented B-57B aircraft are summarized from a meteorological viewpoint in a two-volume technical memorandum. The missions were part of the NASA-Langley Research Center's MAT (Measurement of Atmospheric Turbulence) program, which was conducted from the NASA Langley Research Center (on Langley AFB, VA) and the NASA Dryden Flight Research Center (on Edwards AFB, Calif.) between March 1974, and September 1975, at altitudes ranging up to 15 km. The particular emphasis of this program is to extend power spectral measurements of atmospheric turbulence to wavelengths of at least 9,100 m (30,000 ft) under several meteorological conditions and a range of altitudes of 0-15,240 m (0-50,000 ft). This is important for design of large, structurally flexible higher speed aircraft in addition to the general research need for developing a better insight into the relation between turbulence and basic atmospheric phenomena which may cause it.

Turbulence samples were obtained under diverse conditions including mountain waves, jet streams, upper level fronts and troughs, and low altitude mechanical and thermal turbulence. CAT was encountered on 20 flights comprising 77 data runs. In all, approximately 4335 km were flown in light turbulence, 1415 km in moderate turbulence, and 255 km in severe turbulence during the program. The first volume presents the flight planning, operations, and turbulence forecasting aspects of that portion of the MAT program conducted with the B-57B aircraft, as well as the overall results and recommendations for future turbulence sampling programs. In the second volume (Appendix C), 27 MAT flights of particular meteorological interest are each described by narrative summaries, supplemented in some cases by synoptic maps and rawinsonde sounding data. This has been done in a manner to facilitate correlation with the turbulence time histories and power spectra derived in the project. Some photographs of clouds are also included, in order to show some of the cloud patterns which may serve as visual warnings of turbulent conditions.

APPENDIX C

METEOROLOGICAL SUMMARIES FOR EACH SIGNIFICANT MAT B-57B FLIGHT

This appendix contains a summary description of those flights with the B-57B where turbulence encounter was sought. From the complete chronological listing of Table II in the main section of the report (Volume 1), those flights were selected where the purpose was to sample turbulence, whether or not the turbulence instrumentation was fully operational. Missions where the forecast likelihood of turbulence was poor, and the flight was planned primarily for instrument calibration purposes (e.g., Flight 2) are not reported. Also those flights probing turbulence in the vicinity of thunderstorms are not reported here, because the thunderstorms were of the air mass-type in each case, and it is of no value to describe them on the synoptic scale.

Twenty-seven of the flights are individually described in this section. The description in each case includes: (a) a narrative flight summary, with emphasis on the turbulence sampled along the flight track; (b) a meteorological summary, and (c) a discussion where the most likely explanation for the turbulence encountered (or its absence) is offered. In some cases, figures portraying flight tracks, synoptic analyses, rawinsonde plots, etc., are presented to elucidate details of the missions. Table C-1 is a listing of the flights discussed in this appendix.

TABLE C-1

MAT B57B MISSIONS COVERED BY NARRATIVE SUMMARIES IN APPENDIX C

Mission No.	Altitudes of Turbulence Encounter (km)	Distances in turbc. (km)			Most Probable Met. Condition Associated with Turbulence (or turbc. forecast)	Described by Figures N
		Light	Moderate	Severe		
8	0.5-1.1	300	0	0	Low Altitude Convection	-
9	0.5-1.1	480	0	0	Low Altitude Convection	-
14	-	0	0	0	(Jet Stream, Wind Shear)	C1 - C5
15	8.2-9.1	47	0	0	Upper Trough and Jet Stream	C6
18	9.0	in clouds only			(Mountain Wave)	-
19	5.0-6.0	71	0	0	Low Level Jet with Vertical Wind Shear and Strong Horizontal Temp. Gradient	C7 - C10
20	1-5.5	293	111	14	Appalachian Mountain Wave	C11 - C17
24	5.9	112	1	0	Jet Streams, Strong Shears	C18 - C23
25	9.8-12.5	(patchy very light turbc.)			(Jet Stream Wind Shear)	-
26	9.1-9.5	324	75	0	Upper Trough and Jet Stream	C24 - C30
27	4.7	147	4	0	Low Altitude Jet, Vert. Wind Shear	C31 - C34
28	1.3-2.6	305	168	52	Low Altitude Wind Shear, Orographic Effects	C35 - C39
29	1.2, 7.4, 10.7	323	66	20	Low Level Orographic, Mountain Wave	C40 - C44
30	14.3-14.5	77	0	0	Mountain Wave	C45 - C53
31	8.5-13.5	(patchy)			(Mountain Wave)	-
32	12.0-13.5	331	177	0	Complex Orographic Effects, Wind Shear	C54 - C62
33	1.8-2.8	112	44	0	Low Level Orographic	-
34	4.0-4.4	168	161	70	Low Level Mountain Wave	C63 - C68
35	10.7-13.7	(patchy very light turbc.)			(Mountain Wave)	-
36	-	(none)			(Mountain Wave, Vertical Wind Shear)	-
37	-	(none)			(Trough Wind Shear)	-
38	10.8-11.6	58	0	0	Short Wave Trough, Orographic Effects	C69 - C70
39	3-4.5	453	176	52	Mountain Wave and Intense Upper Front	C71 - C79
40	12.1-12.4	16	0	0	Frontal Passage with Orographic Effects	C80
41	7.3-7.6	230	105	0	Fast Moving Short Wave Trough, Shear	C81 - C88
42	1.6-4.5	464	317	47	Low Altitude Convection/Sea Breeze Convergence	C89 - C91
43	8.8	24	11	0	Dissipating Mountain Wave	-

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Flight 8, June 19, 1974, 1409 - 1532 EDT (1809 - 1932 GMT)

Flight Summary

At this stage of the research program, the principal interest was in obtaining turbulence records for exercising the instrumentation package, regardless of the mode of turbulence generation (i.e. the turbulence sought was not restricted to CAT). In the absence of turbulence - favoring conditions further aloft, other opportunities for turbulence encounter were sought. On the flight day light winds and unstable conditions near the ground resulting from solar heating increased the probability of thermal turbulence in the surface boundary layer. The B-57B flew southwest from Langley AFB to north-central North Carolina and flew back over the same route.

Two runs of approximately 130 and 170 km were taken in light turbulence at 460 m altitude. The turbulence was continuous but showed occasional variations from the mean intensity. The average intensity was greater to the west where the terrain rose higher. A short run was taken near Langley at 1070 m just below cloud bases but the turbulence intensity was not significantly different from that encountered in the lower altitude runs.

Meteorological Conditions

Moderately high pressure existed at 1200 GMT over Virginia accompanied by warm temperatures and relatively weak flow at and near the surface.

The forecast was for a moderate amount of thermal heating by midday. At

500 mb the flow associated with a broad trough in the eastern U.S. weakened to the south of Virginia. Morning winds at 460 m were generally out of the southwest and around 5 m sec^{-1} in southern Virginia and North Carolina, increasing slightly as the day progressed. Superadiabatic layers near the ground were apparent in the aircraft data on climbout. Unstable conditions were still present on the 2315 GMT (1915 EDT) sounding at Greensboro, NC. Scattered to broken cumulus were noted at 1070 m in the flight area.

Discussion

The continuous turbulence of variable intensity, found over mixed farmland, forest cover, and broad rivers, was characteristic of a typical warm summer day in the eastern U.S. Cumulus clouds marked the upper limits of the turbulence which resulted from unstable conditions due to ground heating. Turbulence was not especially intense because of limited effective heating due to high moisture content of the air and heat absorbing properties of the ground cover.

Flight 9, June 20, 1974, 1407 - 1602 EDT (1807 - 2002 GMT)

Flight Summary

The purpose of the flight was essentially the same as that for flight 8, (performed on the previous day) i.e. to obtain long records in thermal turbulence at low altitudes for exercising the turbulence instrumentation. Some basic differences from flight 8 were:

- (1) The day was warmer.
- (2) Both low and high level clouds were more numerous.
- (3) The primary data runs were further to the east and over lower terrain.
- (4) The turbulence intensity was slightly lower.

Two data runs approximately 240 km long were obtained in very light to light turbulence at 460 m, and a short run was taken at 1070 m just below the cloud bases. As with flight 8, the intensities were about the same on the lower and higher runs.

Meteorological Conditions

The center of high pressure at the surface at 1200 GMT was further southward and westward than on the previous day resulting in southwest winds in excess of 15 m sec^{-1} at 450 m along the eastern shores of Virginia, and a warmer temperature forecast for southeast Virginia. The warmer temperatures were somewhat offset by the increase in sky coverage of both low level cumulus and cirrus. Flow at 500 mb was slightly stronger in northern and central Virginia as the trough line moved eastward and curvature increased. Little change was noted in the flow pattern at this level in southern Virginia, however.

The anticipated temperature increase from the previous day materialized but did not seem to have an effect on the turbulence intensity. Convection was greater in the late afternoon; this became apparent towards the end of the flight when very dark shadows were cast by the clouds (heavy thunderstorms occurred two hours after the flight which were associated with a squall line moving in from the west). Cloud bases remained at about 1070 m which was the same height as on flight 8. 0000 GMT winds in the flight area at 450 m were relatively unchanged from those existing 12 hours previously.

Discussion

Despite the increase in surface heating over that of the previous day, the turbulence intensity appeared to decrease. This was likely due in part to the lower height of much of the terrain below the sampling area and also to the increase in cloud cover. Lack of change in the cloud base height gave another indication that turbulence intensity would be expected to be similar to that on flight 8.

Flight 14, November 7, 1974, 1149-1417 EDT (1549-1817 GMT)

Flight Summary

Although the primary purpose of this flight was to check the performance of the inertial platform after a minor repair, the instrumentation system was in general working order and turbulence data collection was possible. The meteorological situation looked very favorable for wind shear turbulence both below and above the jet stream. In addition, several commercial and other pilot reports of turbulence were received prior to the flight from locations west or upwind of the proposed search area.

The B-57B flew west-northwestward from Langley AFB to Gordonsville, VA and Elkins, WV, searching between 8 and 11 km along the route. A few very light bumps were noted at 5.5 and 7.6 km on climbout and at 9.0, 9.5, and 11.3 km in the search between Gordonsville and Elkins. Three data runs were made south and east of Richmond, VA at 9.5, 7.6, and 6.1 km with only a few brief patches of very light turbulence recorded. The descent was in almost totally smooth air, even within the clouds.

Numerous jet aircraft reported turbulence in the eastern U.S. between 0800 and 1400 EDT, especially within 90 to 180 km of St. Louis, Mo., Indianapolis, IN, Lancaster, PA and Albany, NY. Most reports were of light - moderate and moderate turbulence at various levels between 5.5 and 11.9 km.

Meteorological Conditions

The eastern U.S. surface weather at 1800 GMT on the 7th was largely dominated by a high pressure area centered in eastern Missouri. A deep low located 550 km east of Virginia had developed in the previous 12 hours.

Surface winds along the mid-Atlantic states were generally 5 m sec^{-1} from the northwest. Wind speeds at 700 mb on the morning of the 7th were 13 to 20 m sec^{-1} in North Carolina but considerably weaker to the north. A tightly closed circulation in Virginia and surrounding states dominated the 500 mb pattern at 1200 GMT (fig. C-1). Winds were 40 m sec^{-1} a relatively short distance outward from the low center but only 5 to 10 m sec^{-1} over western Kentucky and Indiana. Strong horizontal shear (i.e. change of vector wind over a horizontal distance coordinate) due both to curvature and speed variations existed on the cold as well as warm side of the 500 mb jet maximum. Although the center of a cutoff low at 300 mb coincided with the position of the 500 mb low (fig. C-2), 40 to 50 m sec^{-1} winds covered a broad expanse of the mid-western and eastern U.S. at 300 mb, resulting in large vertical wind shears above the weak wind zones at 500 mb.

The center of the 500 mb low moved rapidly east-northeastward to just off the New Jersey coast and circulation weakened slightly by 0000 GMT (fig. C-3). 500 mb winds in the Virginia area were out of the northwest at 25 to 30 m sec^{-1} . The jet core persisted in the North Carolina region (fig. C-4) and maximum wind speeds increased somewhat. For example, at Greensboro, NC, the maximum speed was 58 m sec^{-1} at 1200 GMT and 71 m sec^{-1} at 0000 GMT.

At 1200 GMT vertical wind shears (i.e. changes of vector wind versus altitude) below the jet stream were $\geq .025 \text{ sec}^{-1}$ ($.025 \text{ m sec}^{-1} \text{ m}^{-1}$) at Wallops Station, VA, Nashville, TN, and Salem, IL while negative shears (i.e. vector wind decreasing with increasing altitude) above the jet were $\geq .020 \text{ sec}^{-1}$ at Cape Hatteras, NC, Greensboro, NC, and Huntington, WV. Shears at Wallops Station had significantly decreased by 0000 GM. when the center of the upper air low was nearer this location. However, shears increased at many stations to the west and southwest of

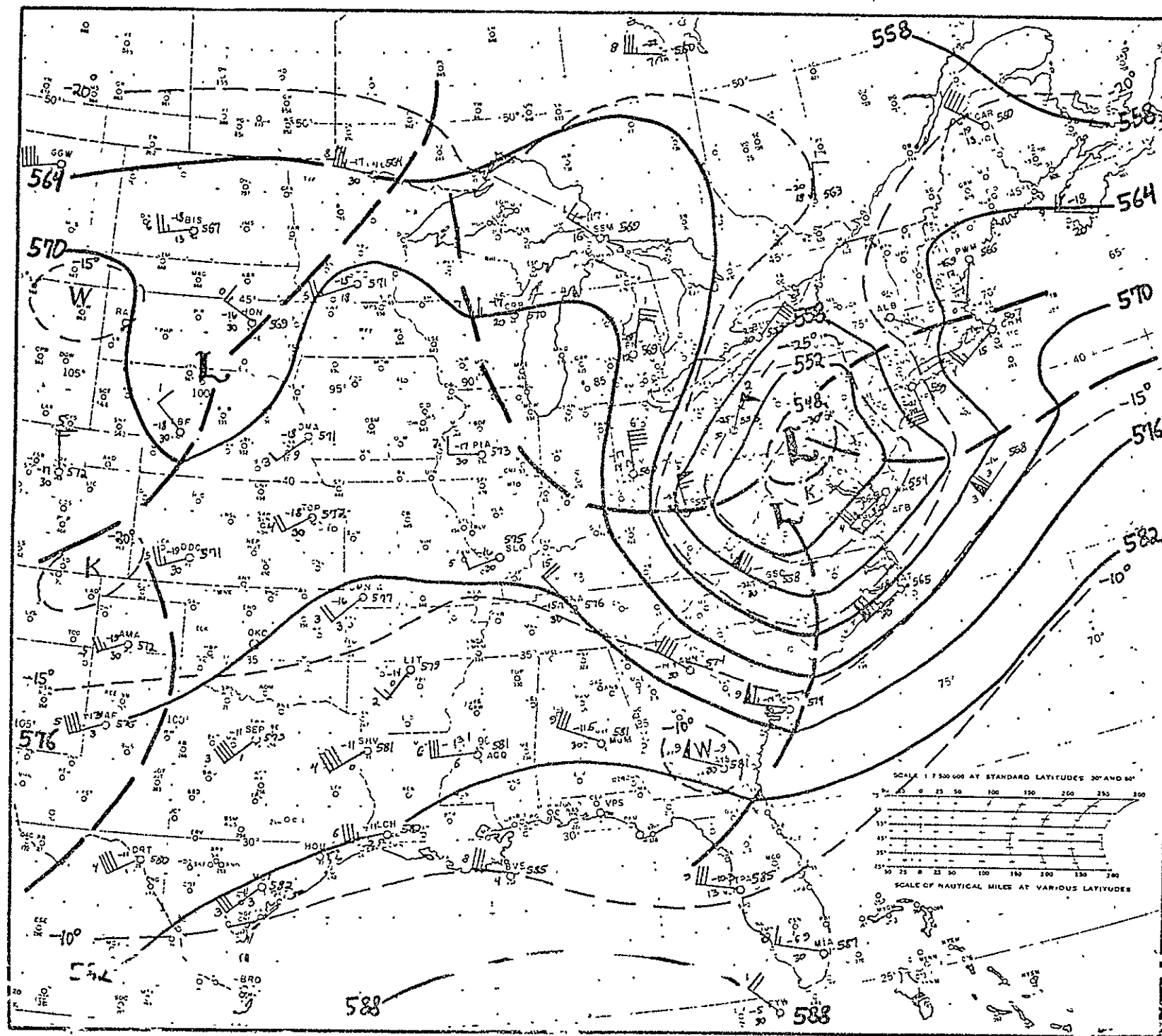


Figure C-1. - 500 mb Analysis, 1200GMT, November 7, 1974. Heights in gndam.

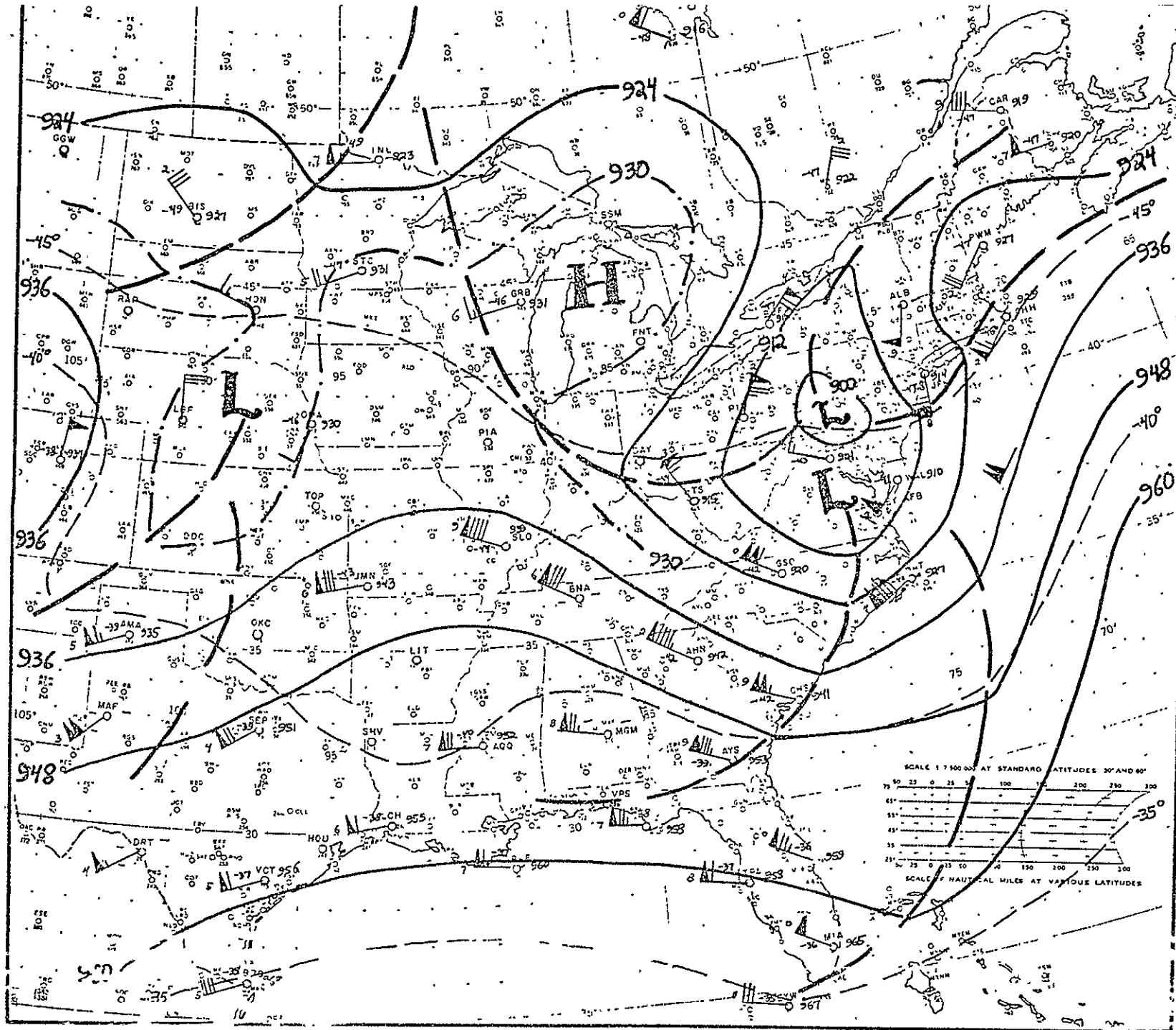


Figure C-2. - 300 mb Analysis, 1200GMT, November 7, 1974. Heights in gpdam.

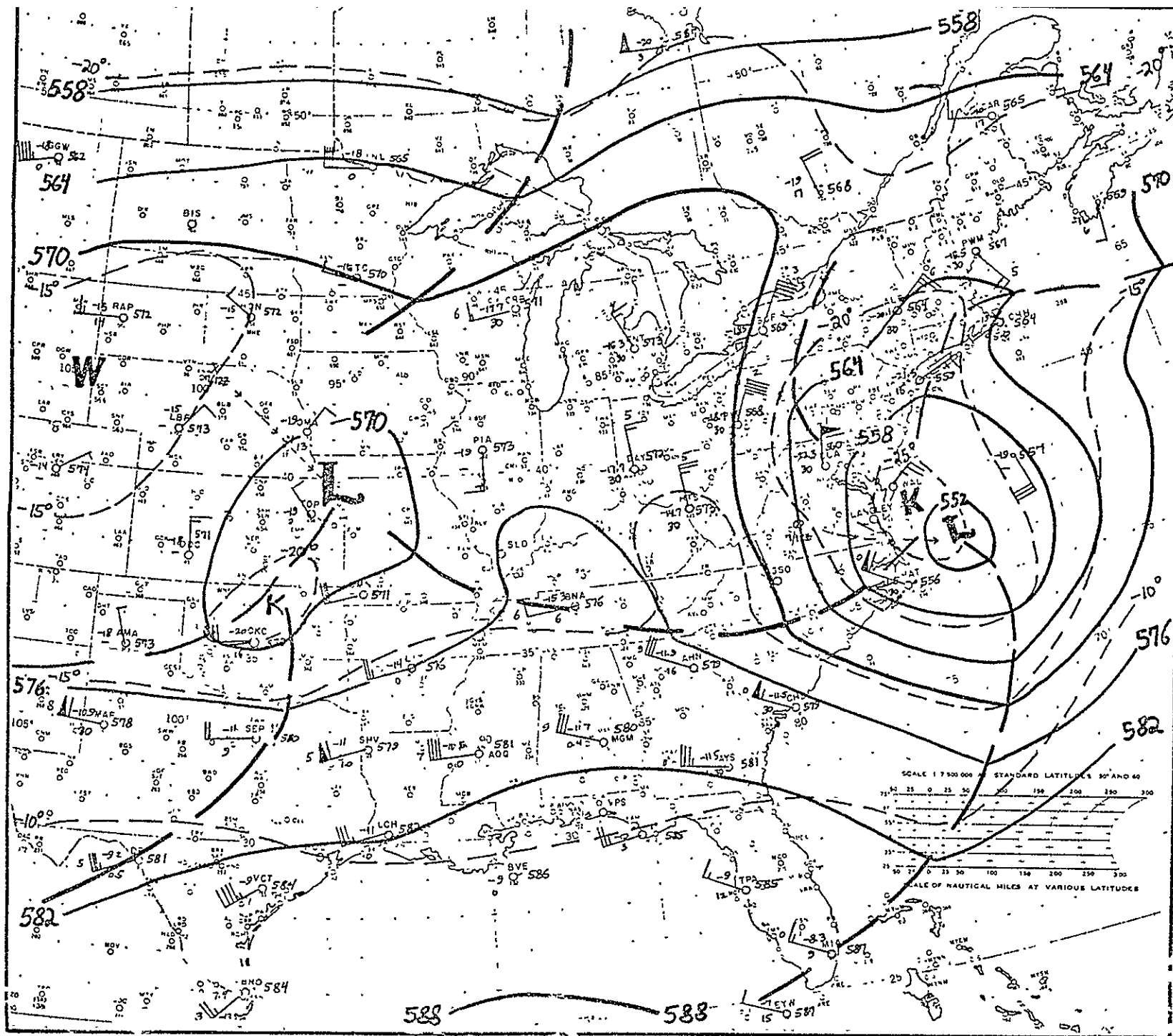
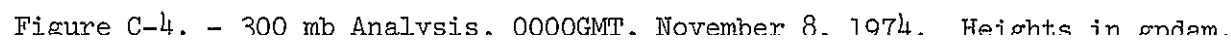


Figure C-3. - 500 mb Analysis, 0000GMT, November 8, 1974. Heights in gpdam.



Virginia with large shears at various levels above 5.5 km, coinciding in part with the altitude range of the pilot reports. However, shears $\geq .034 \text{ sec}^{-1}$ occurred above 12.2 km where aircraft traffic was rather light.

A comparison of 1200 GMT rawinsonde soundings at Greensboro and Huntington (fig. C-5) shows that a slightly cooler environment existed at Greensboro between 3.4 and 7.0 km but considerably higher temperatures were noted there around 11.6 km. As can be seen on the 0000 GMT November 8 Greensboro sounding in figure C-5 warming took place below 7.6 km during the day as the low at 500 mb moved eastward.

Discussion

Strong horizontal and vertical wind shears created by very tight circulation around a mid-altitude low plus super position of the jet stream above weak flow areas was accompanied by numerous turbulence reports from jet aircraft in the midwestern and eastern U.S. The B-57B failed to encounter more than very light chop at any altitude, however, possibly due to bad timing for the particular search area. Also, most of the pilot reports indicated that the turbulence, although fairly intense, was not continuous, which reduced the probability of locating it within the time allotted for the flight. Very little searching was done in the region of large negative wind shears above the jet stream due to the limited fuel available.

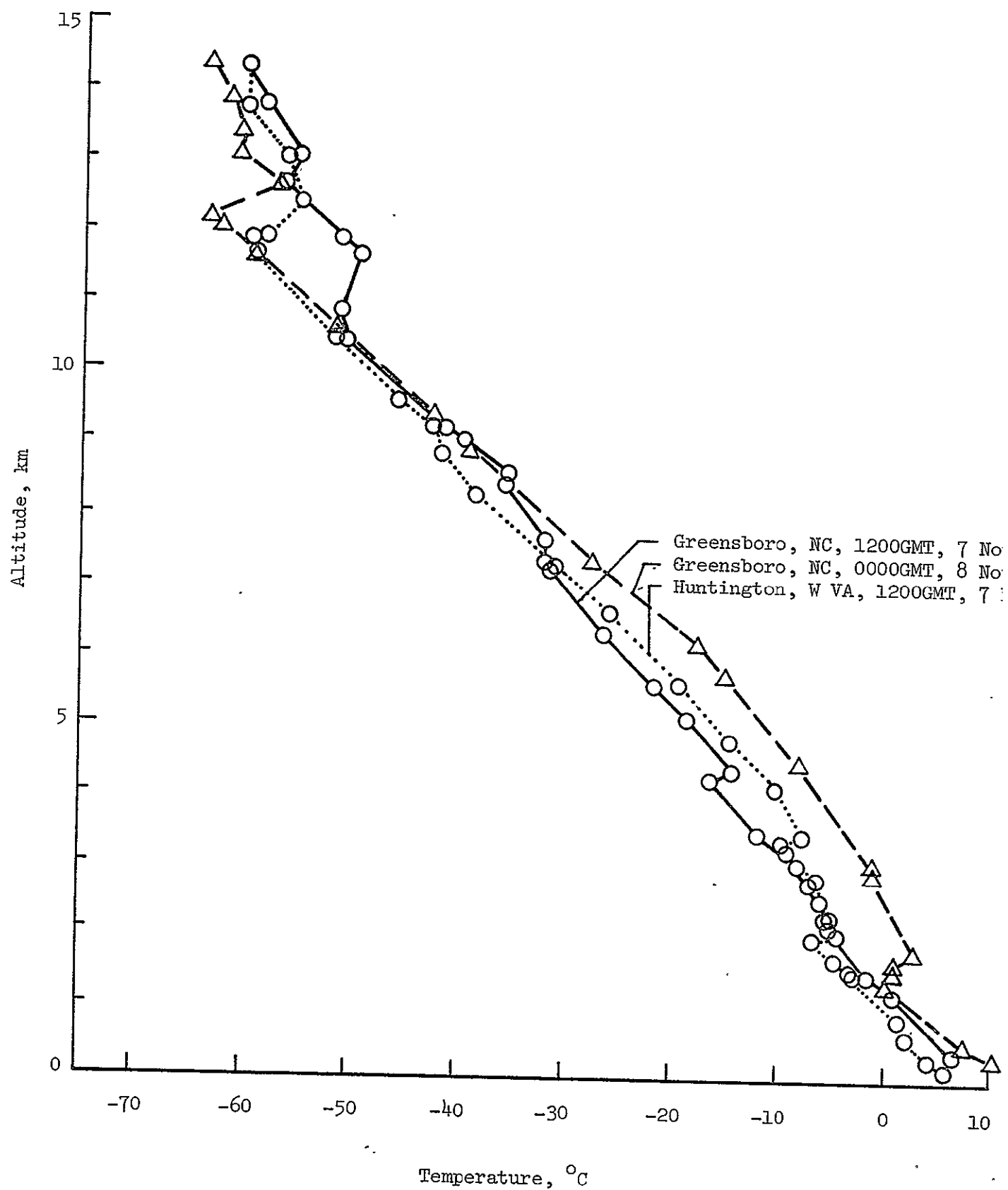


Figure C-5.- Rawinsonde temperature soundings for November 7 & 8, 1974, at Greensboro, NC, and Huntington, W VA.

Flight 15, November 8, 1974, 1143-1427 EDT (1643-1927 GMT)

Flight Summary

The flight plan was to search east of Langley AFB up to 12.2 km for wind shear-related turbulence near the maximum flow curvature in the upper air trough. A short patch of very light to light turbulence was encountered 350 km east-northeast of Langley AFB at 8.2 km, 600 m above some cumuliiform perturbations in a cirrostratus layer. Light turbulence occurred briefly, again at 8.2 km, in cirrus clouds 122 km east of Norfolk, VA on the return towards Langley AFB. A commercial pilot report was received of turbulence in cirrus to the south-southwest of Norfolk, VA as the B-57B approached Norfolk. The area was investigated and a run was made within an extended cirrus cloud which extended at least 35 km at 9.1 km, parallel to its long dimension (215° track), in continued very light to light turbulence. A return run was made (035° track) 300 m higher, in and out of the cloud tops. Turbulence was more patchy than on the previous run and more intense when the aircraft flew within the cloud. Other than the turbulence already mentioned, only a few patches of very light turbulence occurred on the flight, all in the 7.0 to 10.1 km altitude band. There were several military and commercial pilot reports of moderate and greater turbulence between 4.6 and 10.7 km, generally located in the South Carolina-Georgia and New Jersey areas, in a 5 hour period encompassing the time of the B-57B flight.

Meteorological Conditions

A deep 992 mb surface low, which had developed rapidly over the Atlantic during the 12 hours preceding 1200 GMT, was located 550 km east of New Jersey. Pressures were rising along the Virginia-Maryland coast and surface winds at flight-time were around 5 to 8 m sec⁻¹ out of the north. An upper level cutoff low, which had moved fairly rapidly from the west, was located 275 km to the west of the surface low at 500 mb and was filling quite rapidly. Strongest horizontal wind shears in the jet stream region were to the south and southwest of Virginia. Some convergence of the upper level winds existed 275-370 km east of Virginia. Speeds, however, were only 15 to 26 m sec⁻¹ at 300 mb along the Atlantic coast winds along the mid-Atlantic coast had maximum speeds near 10.7 km, increasing towards the south. Wallops Station, VA had a maximum wind of 327°/30 m sec⁻¹ and Cape Hatteras, NC 287°/48 m sec⁻¹. Vertical shears at Hatteras were .029 sec⁻¹ between 5.8 and 6.1 km and .020 sec⁻¹ at several levels between 6.1 and 11.3 km. Considerably less vertical shear existed to the north in the area of lighter wind speeds. The tropopause wind and height prognosis which was valid at or around flight-time, showed a moderately steep height gradient along the North Carolina-South Carolina coast and maximum horizontal wind shears 370 km east of the Virginia-North Carolina border. The probability of turbulence appeared highest off the New Jersey-Maryland coast below 10.7 km. Little movement was expected for the upper level low center in the 12 hours following 1200 GMT.

A 15 degree shift in the wind direction was noted during the turbulent portions of runs 1 and 6. In both cases, the change occurred over a distance of only 7 km, suggesting a localized area of convergence.

Temperature soundings constructed from climbout and descent data (fig. C-6) show that rather unstable conditions existed at the level where the heaviest turbulence occurred. Considerable cloudiness lay over the Atlantic east of Virginia during the flight. The western border of the clouds was located around 110 km east of Norfolk. Tops were estimated at 3 km. Several layers of cirrostratus clouds were noted throughout the flight between 8.2 and 9.1 km. All the cirrus clouds penetrated by the B-57B were associated with some turbulence.

Discussion

Because the upper-level low over the Atlantic was filling quite rapidly, the likelihood of obtaining turbulence was not considered very promising. However, vertical wind shears of sufficient magnitude to be associated with turbulence existed southwest of the cutoff low where jet stream winds overlay a region of moderately weak winds near 500 mb. A relatively unstable layer was also present in this region and was identified by both cirrostratus clouds and turbulent air.

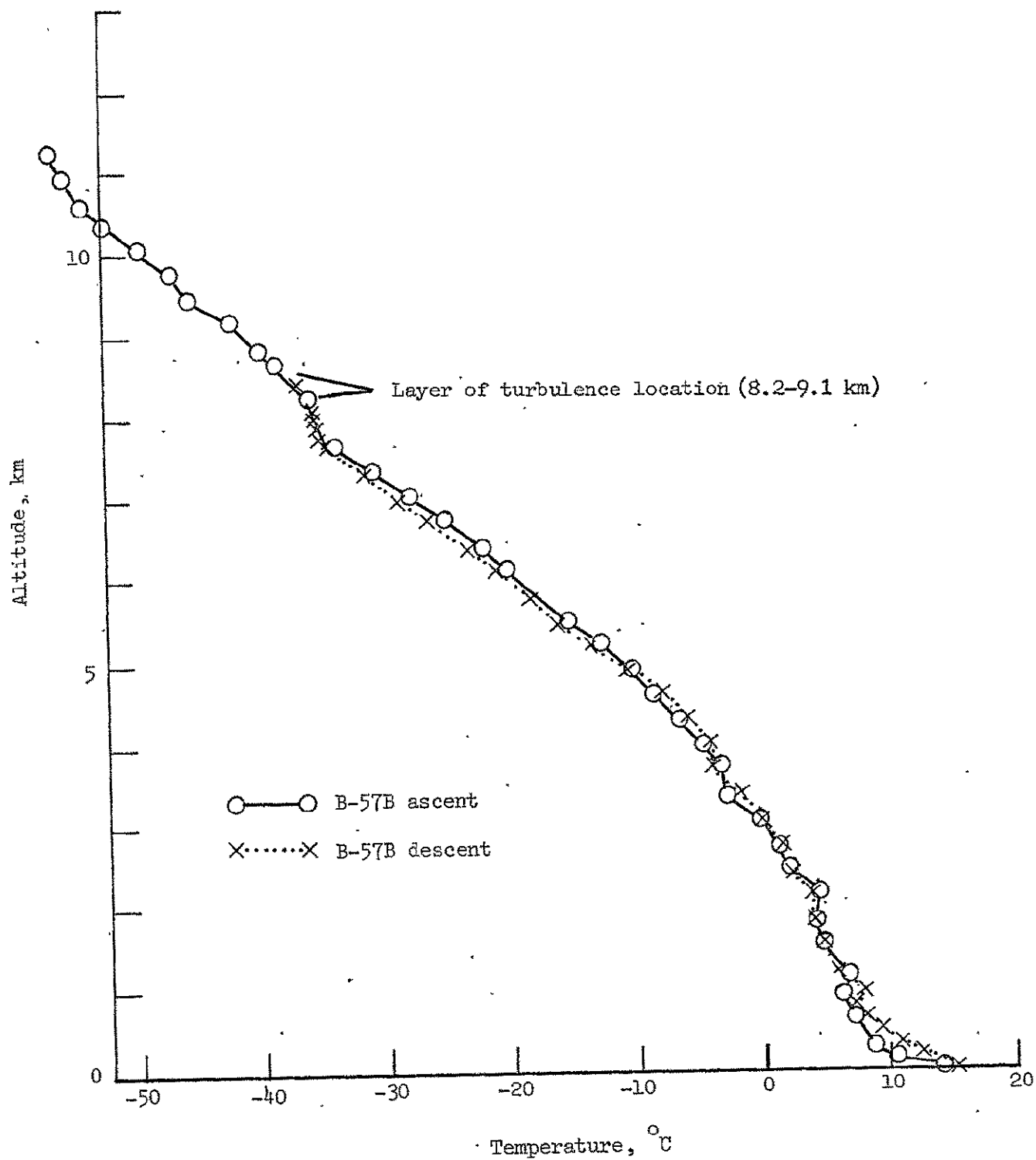


Figure C-6.- Climbout and descent temperature soundings for Flight 15.

Flight 18, November 21, 1974, 1430 - 1540 EST (1930 - 2040 GMT)

Flight Summary

Flight 18 took place on the afternoon of November 21. The plan was to probe for mountain-generated turbulence near the jet stream and, if time permitted, descend to low levels in search for orographically induced turbulence east of the Appalachian ridges. When the B-57B reached the intended search area, ATC directed the aircraft into an extensive cirrostratus cloud at 9.0 km, located 93 km north of Lynchburg, VA, where a Boeing 727 had just reported moderate turbulence. Rather steady light to moderate turbulence was encountered in the cirrus. The flight had to be aborted, however, before data was taken because of a problem relating to transfer of fuel. On the descent some light turbulence was observed near Richmond at 7.3 km directly over a wave cloud which had formed at 3.0 km altitude.

Meteorological Conditions

An upper air trough located in the eastern U.S. was forecasted to move eastward. Jet stream level winds were expected to increase in the Appalachians during the day and shift from west-northwest to northwest. With the extensive surface low system remaining nearly stationary until flight time, low level winds continued to exceed 15 to 20 m sec^{-1} from the northwest, making conditions for mountain waves quite favorable at low elevations and a strong possibility at higher levels. Cape Hatteras and Greensboro, NC had vertical wind shears of 0.024 sec^{-1} in the 8.5 to 9.1 km layer. Huntington, WV, west of the search area, had shears of only

$.009 \text{ sec}^{-1}$ within and near this layer. Wind speeds and shears increased at Huntington, however, as the trough moved eastward. Speeds changed from $320^\circ/27 \text{ m sec}^{-1}$ at 1200 GMT to $352^\circ/66 \text{ m sec}^{-1}$ at 0000 GMT at 9.1 km and vertical shears reached 0.034 sec^{-1} at 0000 GMT between 7.6 and 8.7 km. Mountain wave activity was visually evident at low levels on a 1400 GMT satellite photograph showing several parallel bands of clouds over and east of the Appalachians. Isolated lenticular clouds were present on the flight from the mountains northwest of Lynchburg to east of Richmond and numerous wave clouds were imbedded within long parallel rolls of stratocumulus in the vicinity of the mountains. The elongated cirrostratus cloud within which the light-moderate turbulence was found north of Lynchburg was oriented along the direction of the mountain ridges, suggesting that its presence was orographically influenced. During the flight period, the cloud cover east of the mountains was observed to decrease significantly from nearly overcast to scattered.

Discussion

Lenticular clouds and bands of stratocumulus clouds parallel to the mountains were indications of mountain wave activity. Movement of the upper trough eastward, accompanied by an increase in jet stream winds and vertical wind shear, appears to have influenced the production of turbulence in the mountain areas. The altitude where the most intense turbulence was found coincided with a local region of maximum vertical shear at three stations plus several pilot reports of turbulence in the southeastern U.S. Some pilot reports were in areas well clear of any mountain influence which makes it questionable whether the mountains were the major factor in the presence of turbulence near the Appalachians north of Lynchburg.

Flight 19, November 26, 1974, 1130-1337 EST (1630-1837 GMT)

Flight Summary

The flight was the first in the program to encounter a sizeable patch of turbulence in a forecasted region at jet stream altitudes. Very light to light turbulence was found within a 50 km wide area over the ocean, centered approximately 175 km east of Cape Charles, at an altitude of 5.9 km (fig. C-7). A small area of light turbulence was also noted 32 to 48 km southeast of Cape Charles on climbout and on the return leg to Langley AFB, both at 5.5 km. No organized flight pattern was used because of the patchy nature of the turbulence. Extensive vertical searching took place below 9 km and significant turbulence was found between 5 and 6 km. A planned search in the primary forecast area (north to northeast of the ultimate data gathering location) was abandoned when turbulence, initially encountered on climbout, was found to decrease towards the northeast from Cape Charles.

Meteorological Conditions

The influence of a deep surface low (central pressure of 987 mb), moving slowly eastward near Nova Scotia at 1200 GMT (fig. C-8), was felt along the mid-Atlantic coast where northwest winds exceeded 10 m sec^{-1} . The winds were forecasted to weaken after 1200 GMT as a high pressure area south of the Great Lakes migrated eastward. Flow at upper levels was also northwesterly along the coast but backed sharply towards the west offshore (fig. C-9). The jet stream was moderately strong and low altitudes, with winds in excess of 50 m sec^{-1} at 5 km over Wallops Station, Va. Large positive vertical shear regions (i.e. wind speed increasing with altitude) existed here between 4 and 5 km and negative shears (i.e. wind speed decreasing with altitude) above 11 km. Increased shear and vorticity due to horizontal wind

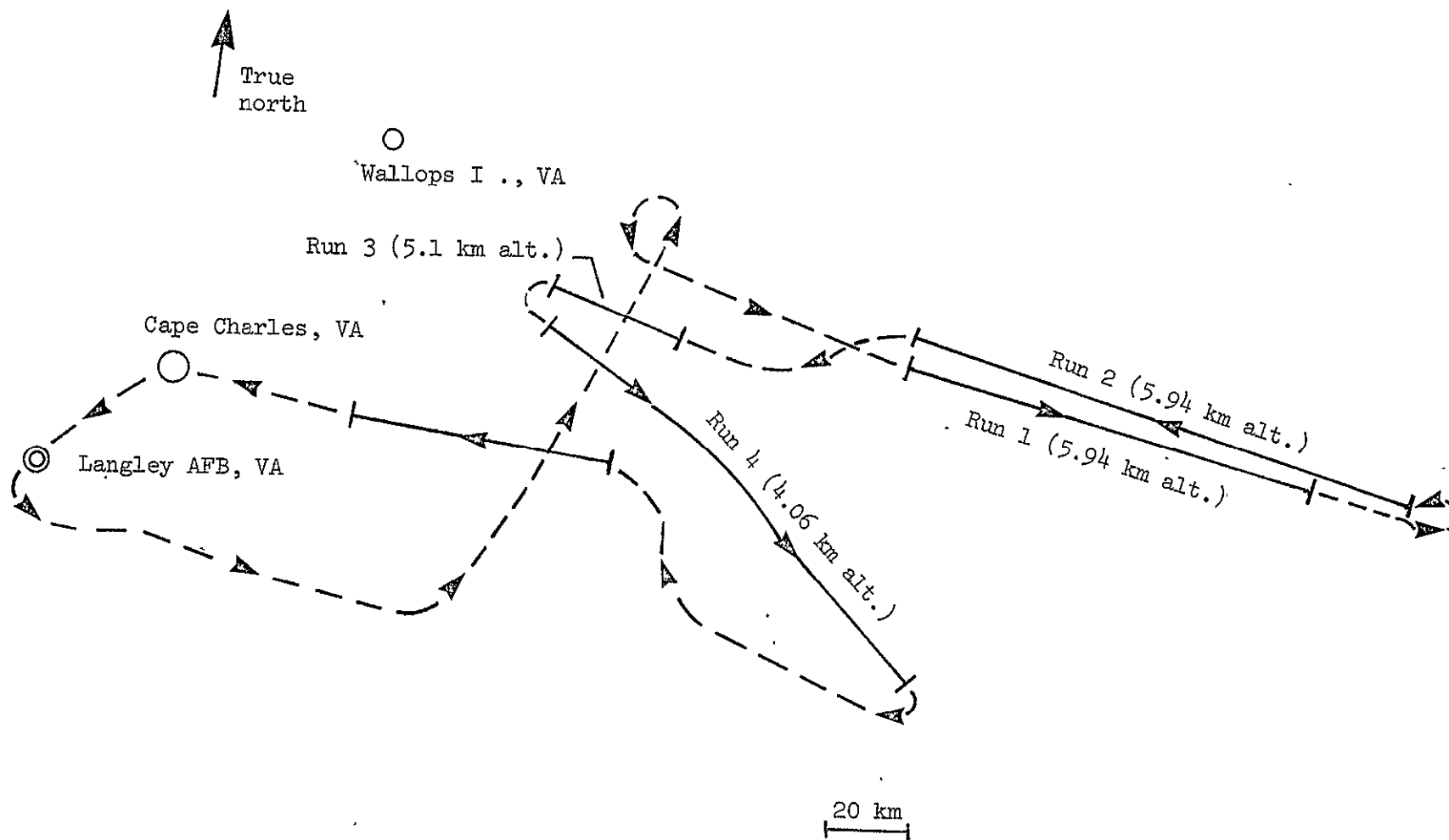
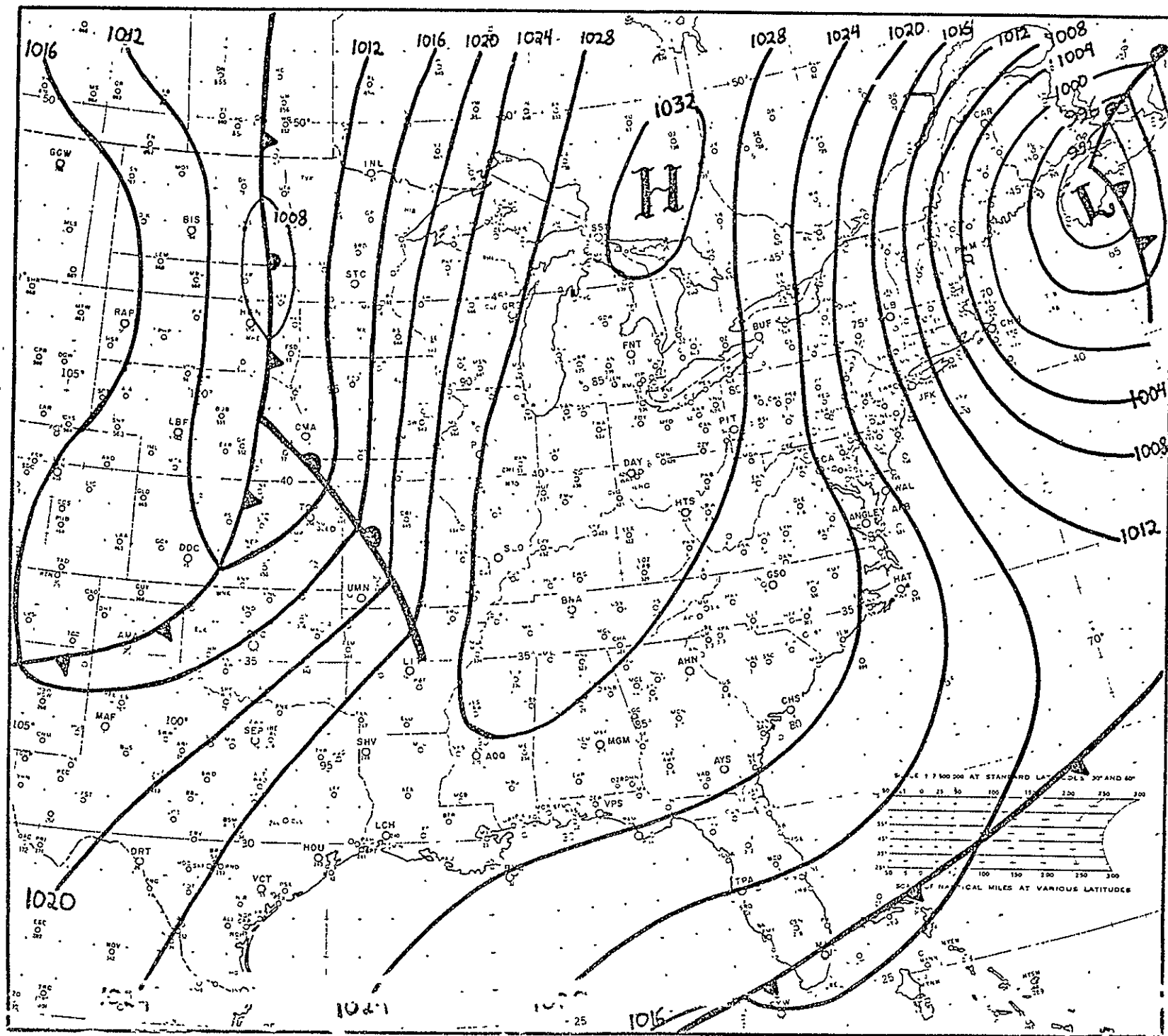


Figure C-7.- Track for Flight 19, 1630-1837 GMT, November 26, 1974.



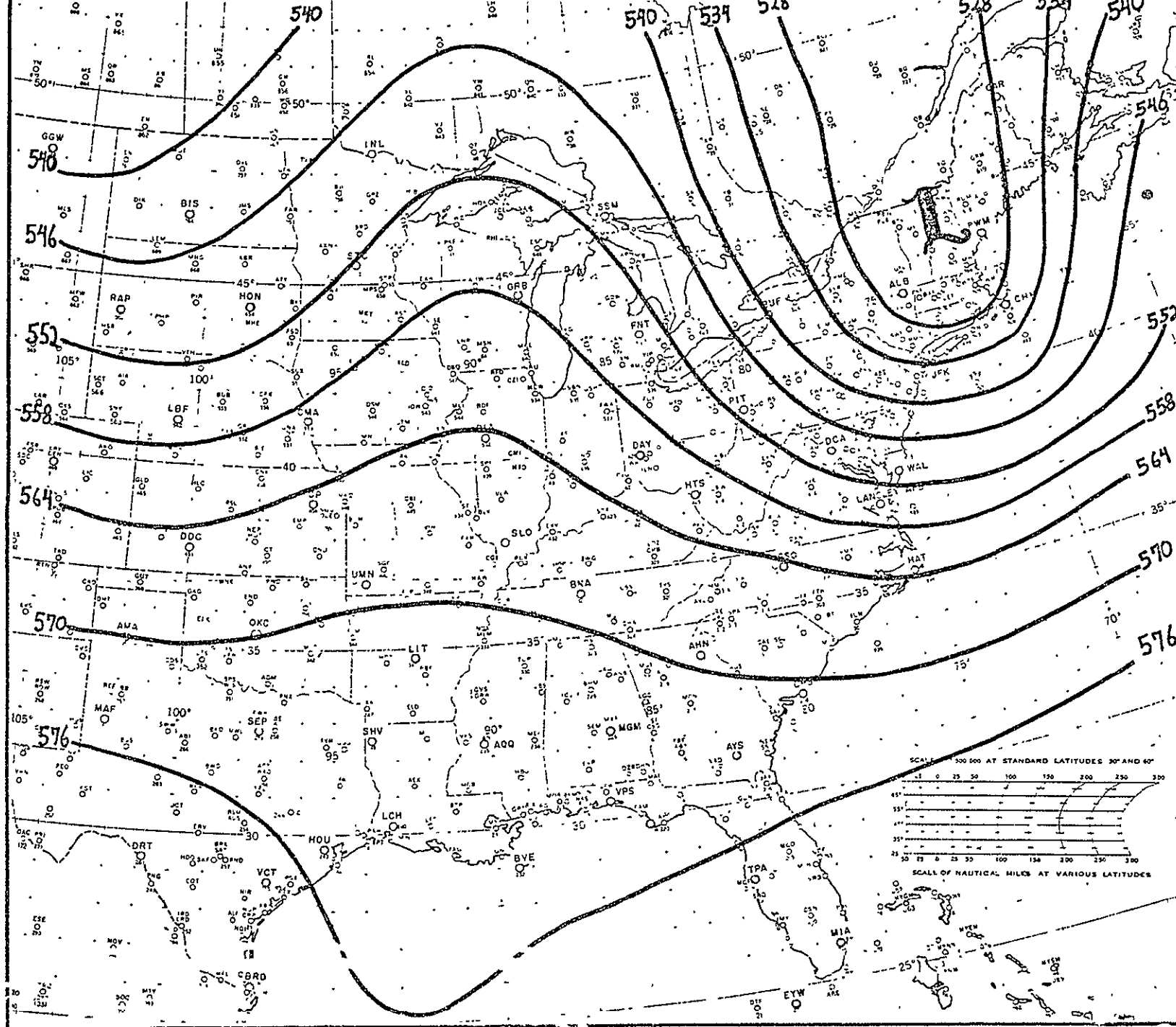


Figure C-9. - 500 mb Height Contours, 1200GMT, November 26, 1974. Heights in gpdam.

direction change was anticipated offshore, especially northeast of Wallops on the eastern side of the narrow trough.

Much of the turbulence occurred at 5 km or slightly higher than the altitude which contained the maximum positive shear at Wallops. This altitude is identified by a stable layer in the search area sounding (fig. C-10). Wind measurements calculated from aircraft track positions indicated that the turbulence was located east of a wind shift from northwest to southwest. A comparison of B-57B sounding temperatures to Wallops and Hatteras rawinsonde data (fig. C-10) shows that a substantial horizontal temperature gradient centered around 3.7 km existed along the mid-Atlantic coast.

Discussion

The turbulence zone appears to have been related to a combination of sharp curvature in the flow field and vertical wind shears near the lower boundary of a low level jet. It is not clear whether a significant relation existed between the turbulence and a large horizontal temperature gradient noted at lower altitudes.

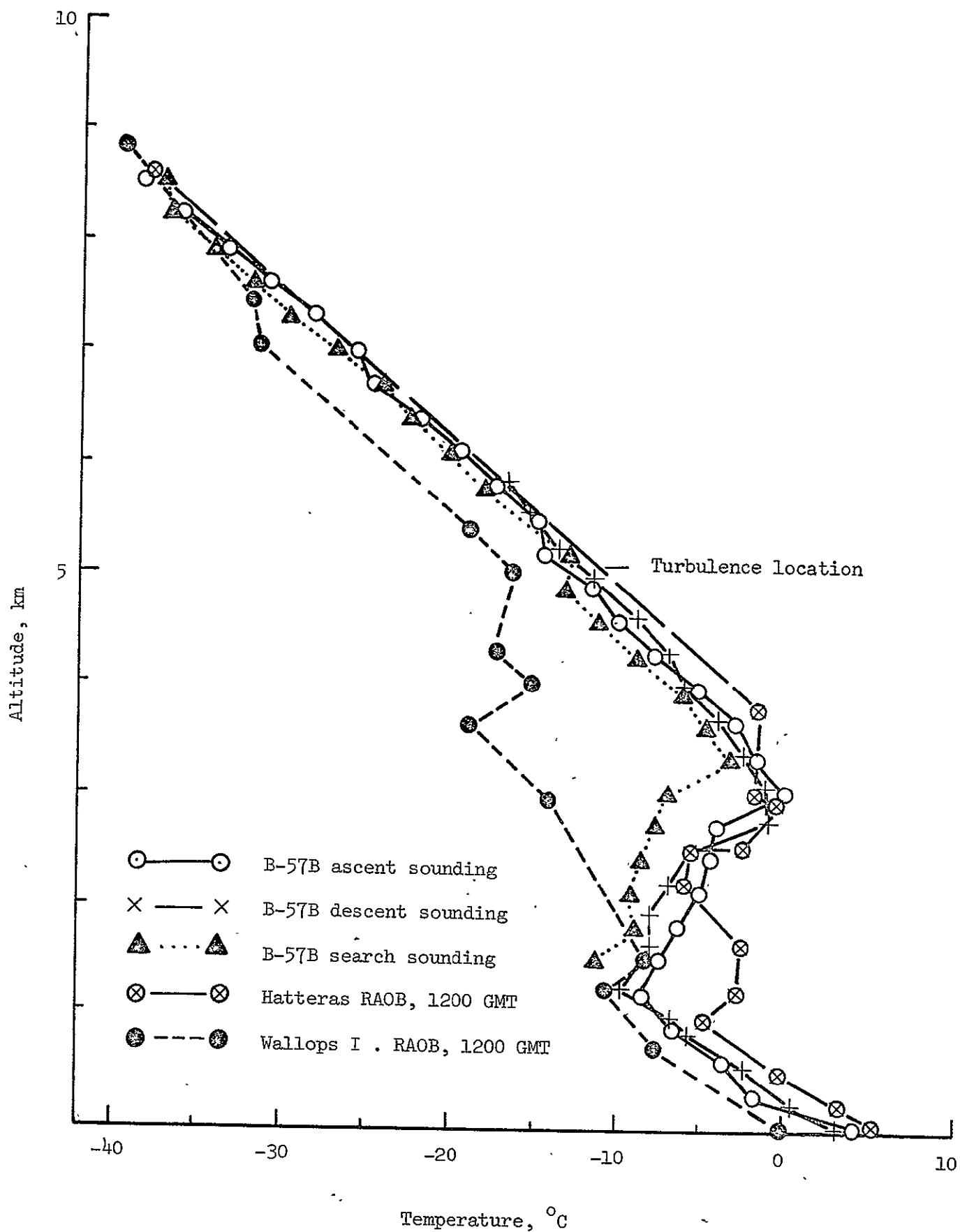


Figure C-10.- MAT B-57B, Hatteras, NC, and Wallops I., VA temperature soundings for Flight 19, November 26, 1974.

Flight 20, 3 December 1974, 1146-1359 EDT (1646-1859 GMT)

Flight Summary

A strong northwesterly windflow orthogonal to the Appalachian ridges made conditions quite favorable for low level mountain wave turbulence. Plans were to cruise at 5.5 km altitude, then descend on the lee, or eastward of the Blue Ridge mountains in western Virginia until a level was reached with fairly intense turbulence. The B-57B completed a mountain wave pattern at 2.0 km, starting the first run 37 km south of Waynesboro, VA (fig. C-11). One leg (run 1) was flown against and one (run 2) with the wind; run 3 was oriented diagonal to the ridges and runs 4 and 5 were parallel to the ridges. Turbulence was highly variable in intensity, especially during runs 1-3 which traversed the ridges and valleys. Most of the areas with moderate or greater turbulence lay 9 to 29 km to the lee of prominent ridges and in the troughs of the mountain waves. Strong up- and downdrafts were noted throughout the pattern. Flight over ridges, especially the eastern-most one in the Appalachians, and over most of the Shenandoah Valley, was usually characterized by smooth air. Runs 4 and 5, parallel to the ridges, were in almost continuous turbulence of highly variable intensity. Both runs had 55 km sections of unbroken turbulence ranging from light to severe in intensity. On run 5 there was one patch approximately 9 km long of severe turbulence with peak cg accelerations exceeding 1g. Above the pattern altitude moderate turbulence was encountered near 2.7 km just prior to the start of run 1 and some very light bumps were noted 55 to 110 km west of Richmond, VA at 5.2 km.

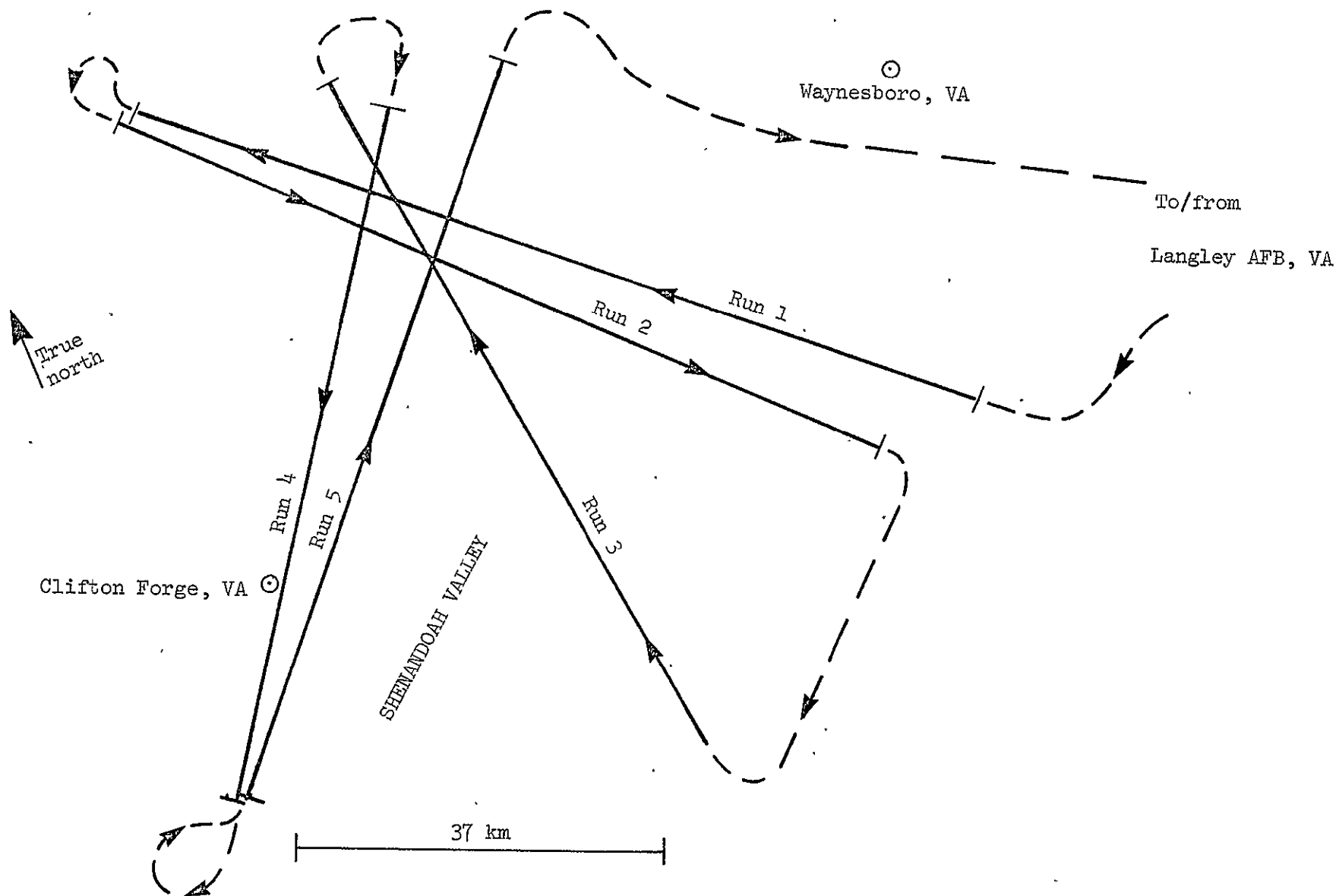


Figure C-11.- Appalachian Mountain wave investigation track for Flight 20, 1646-1859 GMT, December 3, 1974. Altitude on all runs approximately 2 km.

Meteorological Conditions

At 1200 GMT a surface low of 983 mb in southwest Maine which had moved rapidly north along the Atlantic coast in the previous 24 hours, dominated the flow pattern for several hundred km outward from its center. The low continued to move north-northeastward and deepen, reaching 974 mb central pressure at 1800 GMT. (fig. C-12). Winds across the Appalachians exceeded 20 m sec^{-1} on the morning of the 20th and maintained their strength throughout the day. Northwesterly flow, perpendicular to the ridges, existed at 850 and 500 mb (figs. C-13, 14) but became west-northwesterly at jet stream altitudes. Wind shears of $25 \text{ m sec}^{-1} \text{ km}^{-1}$ ($.025 \text{ sec}^{-1}$) and greater were present near the surface at Wallops Station, VA, Washington, DC, and Greensboro, NC at 1200 GMT. Several stations in the mid-Atlantic coastal region recorded strong inversions below 1.8 km (fig. C-15). Zones of minimum wind appeared 1.2 to 3.7 km above the surface at many stations; this situation considerably reduced the changes for mountain waves' projecting to higher altitudes. A B-57B sounding, taken near Charlottesville, VA just prior to the first data run (run 3), showed a windspeed of 22 m sec^{-1} at 2.1 km altitude, with a decrease to 13 m sec^{-1} at 2.8 km. The layer between 2.0 and 2.1 km contained a sharp inversion ($+4.2^\circ \text{ C}$ in 50 m), an 8 m sec^{-1} windspeed increase, and a Richardson number (Ri) of 0.8. Most of the area west of the mountains was cloud-free during the flight and only a few scattered cumulus clouds existed to the east.

On data runs 3, 5, and 6, which were oriented approximately 90° , 85° , and 50° respectively to the primary ridges of the Appalachian chain, wave-like variations in the temperature occurred with amplitudes of 6 to 8°C and



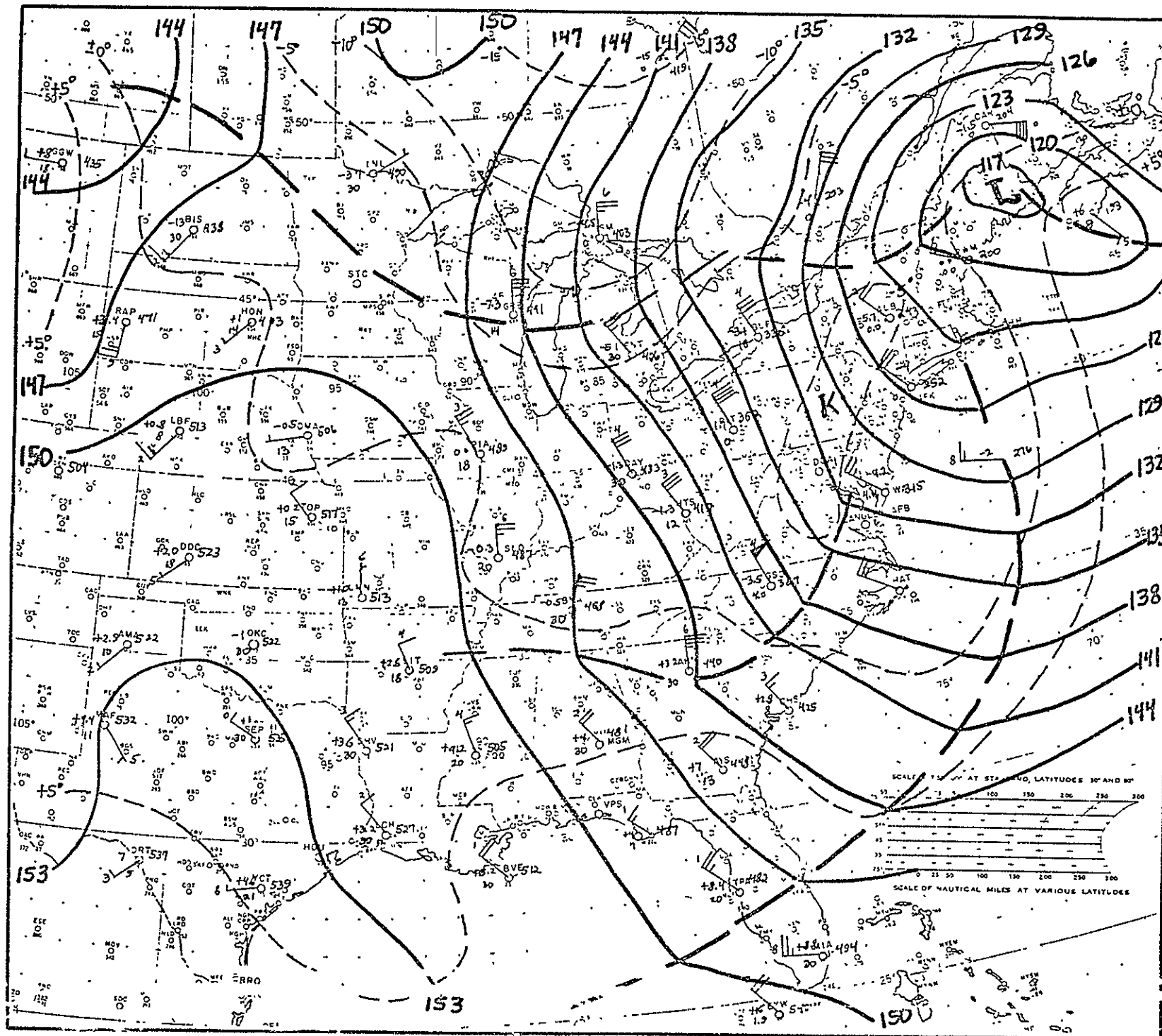


Figure C-13. - 850 mb Analysis, 1200GMT, December 3, 1974. Heights in gpdam.

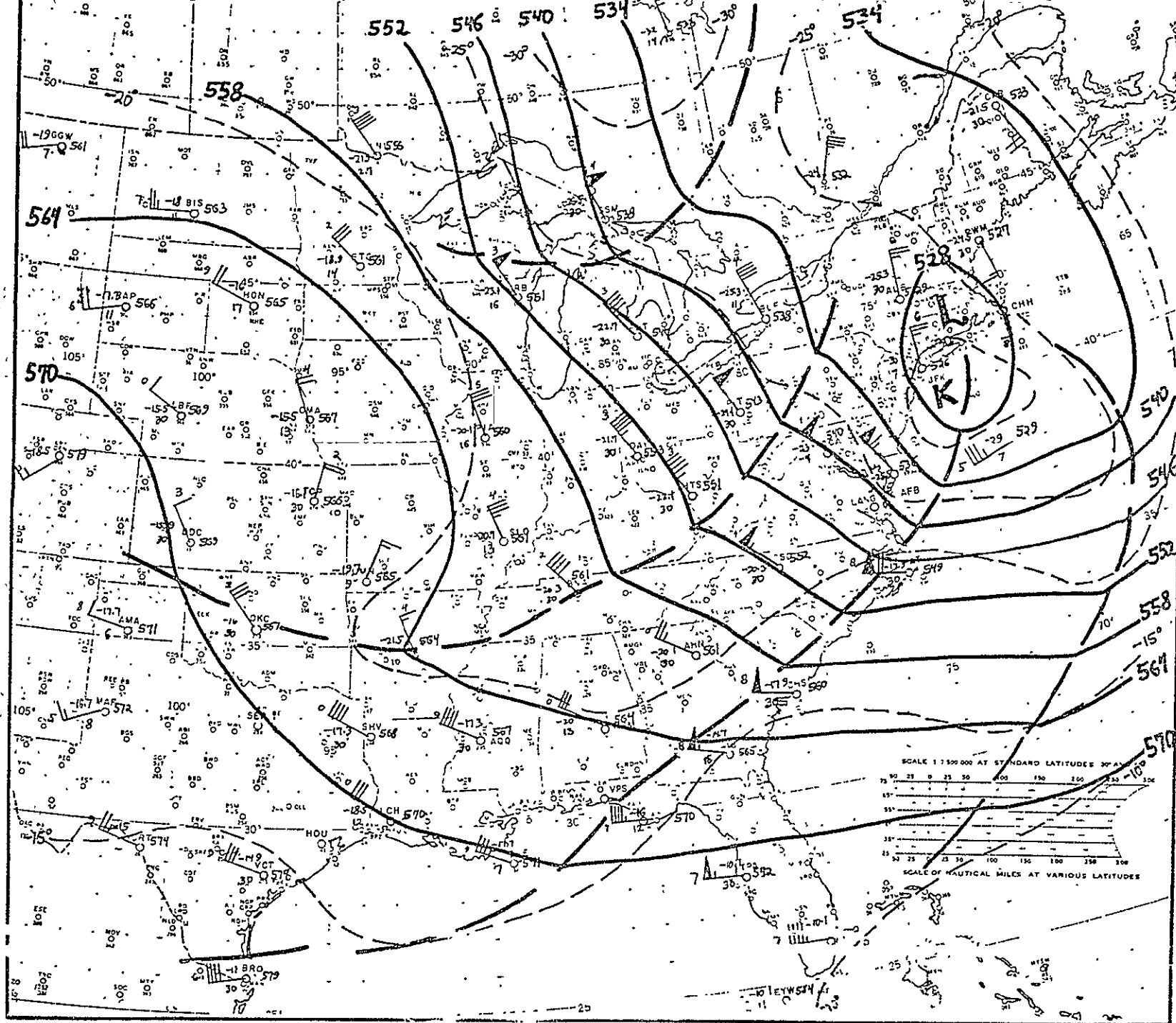


Figure C-14. - 500mb Analysis, 1200GMT, December 3, 1974. Heights in gpdam.

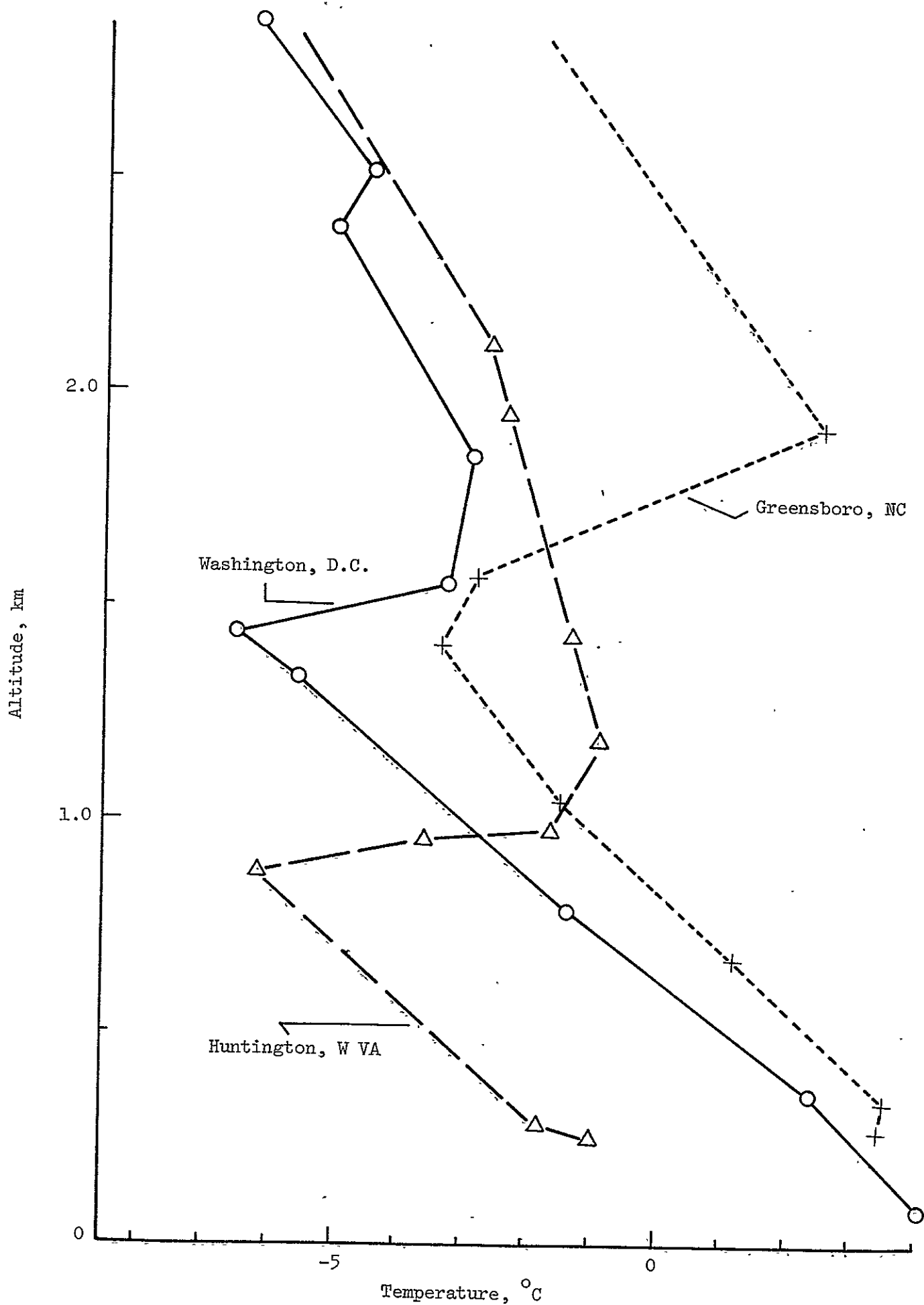


Figure C-15.- Rawinsonde temperature soundings, 1200 GMT, December 3, 1974.

wavelengths ranging from 8 to 18 km (figs. C-16 and C-17). The wave structure was well defined in the smooth areas but appeared to break down within the moderate to severe turbulence patches. Higher temperatures were noted at the beginnings and ends of runs 7 and 8 which were nearly parallel to the ridges. The centers of the runs cooled by 4 to 6°C. This indicates that these runs traversed one wave cycle. Wind speeds during the five turbulence data runs varied between 23 and 28 m sec⁻¹ with highest values occurring in the warm zones (i.e., wave troughs).

High frequency temperature changes were prevalent within the more turbulent portions of the runs, the largest being on the order of 6°C in 300 m.

Discussion

The intense low level mountain wave turbulence found in the lee of the Appalachian ridges in Virginia was related to strong winds orthogonal to the ridge lines, sharp temperature inversions near the ridge levels, and large magnitude wind shears near the ridge levels.

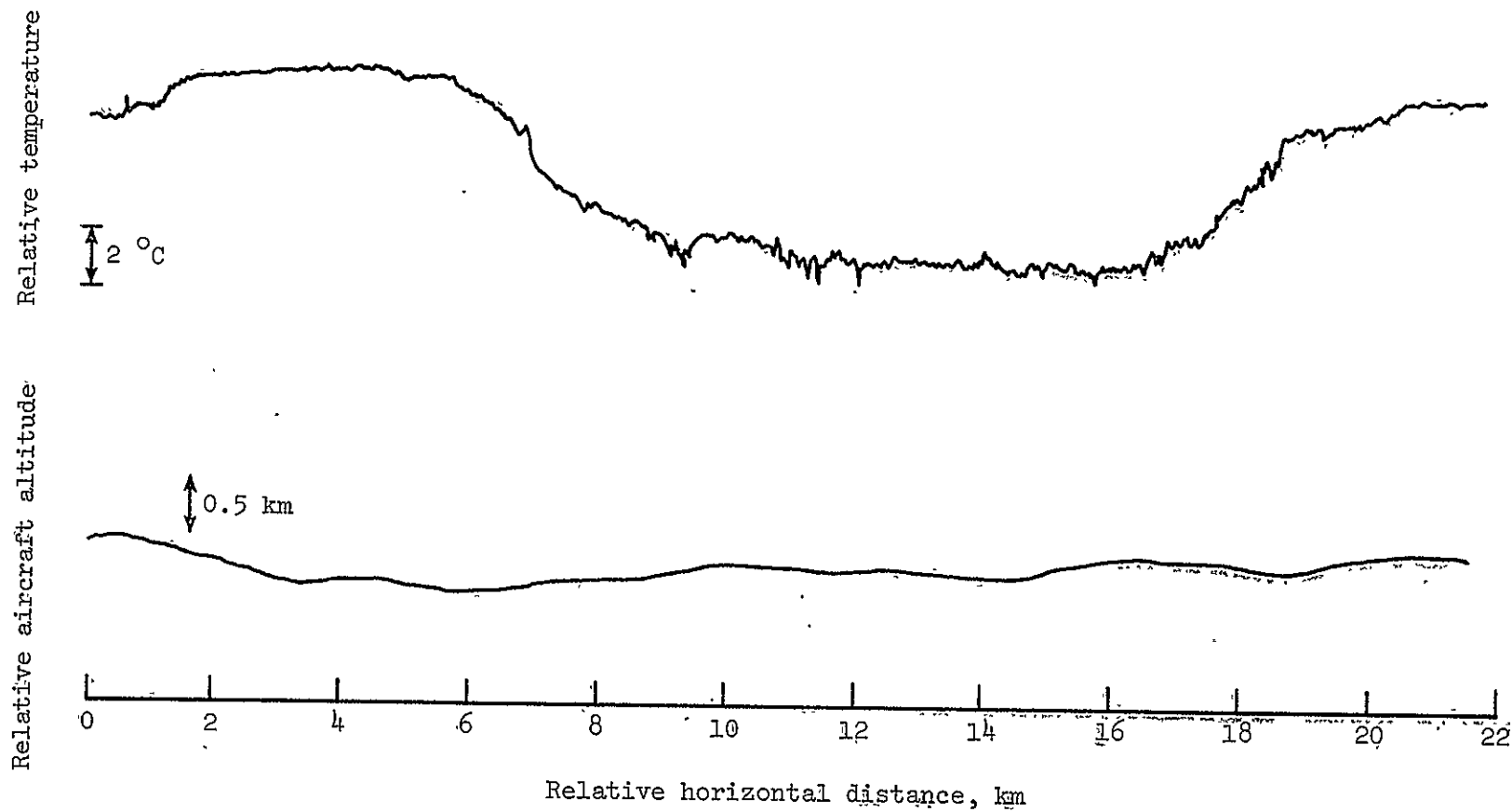


Figure C-16.- Wave structure in temperature pattern on run 3 of Flight 20.

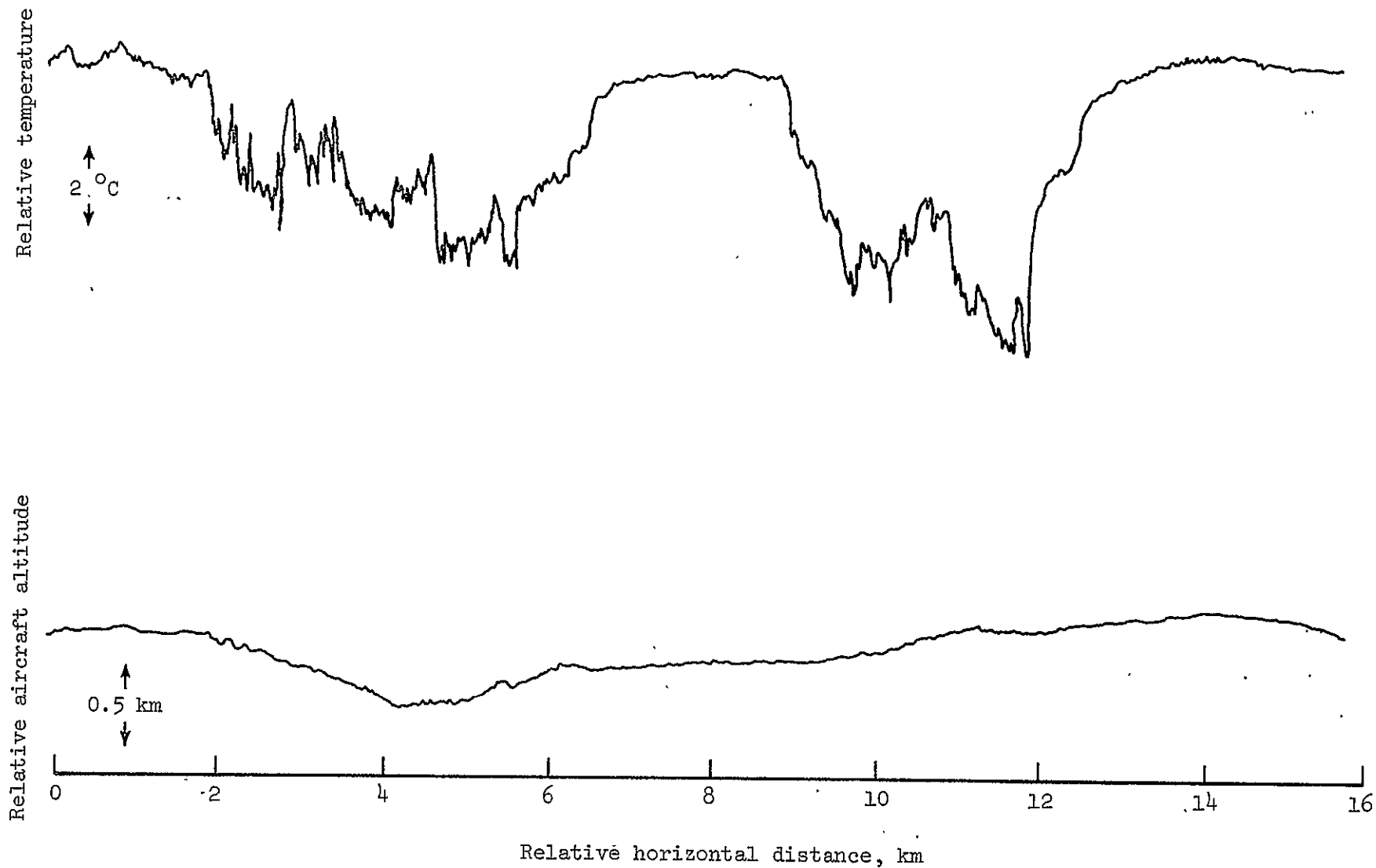


Figure C-17.- Wave structure in temperature pattern on run 6 of Flight 20.

Flight 24, December 17, 1974, 1112-1304 EST (1612-1804 GMT)

Flight Summary

Large vertical and horizontal wind shears, observed along an extended zone of the Atlantic coastal states, were major factors in raising the probability of jet-stream-related turbulence to the highest level since the start of the MAT program. Numerous commercial and military aircraft pilot reports of moderate turbulence were received, primarily from New Jersey, Delaware, and southeastern Pennsylvania near 6 km altitude. Two aircraft reported moderate turbulence in the search area near 6 km, 2 to 3 hours before the B-57B flight, one 90 km southwest of Greensboro, NC, and the other over Danville, VA. The flight was directed, therefore, to an area between north-central North Carolina and central Virginia because of its proximity to Langley AFB. This decision increased the chances of more search and sampling time possibilities and presented fewer problems with airline traffic. The search was conducted from the approximate location of these reports to an area 110 km north of Langley AFB (fig. C-18) where a Boeing 727 had reported an encounter with moderate-severe turbulence between 5.5 and 6.7 km. All runs were made at 5.9 km. The turbulence recorded during the flight was generally very light. A few light and occasional light-moderate patches were encountered but these appeared to be random in location. The most intense and continuous turbulence was found on the eastern side of the search area (runs 7 and 9) within or very close to cirrostratus clouds. Run 8 was parallel to the edge of a lenticular-shaped altocumulus cloud located approximately 3 km below the aircraft.

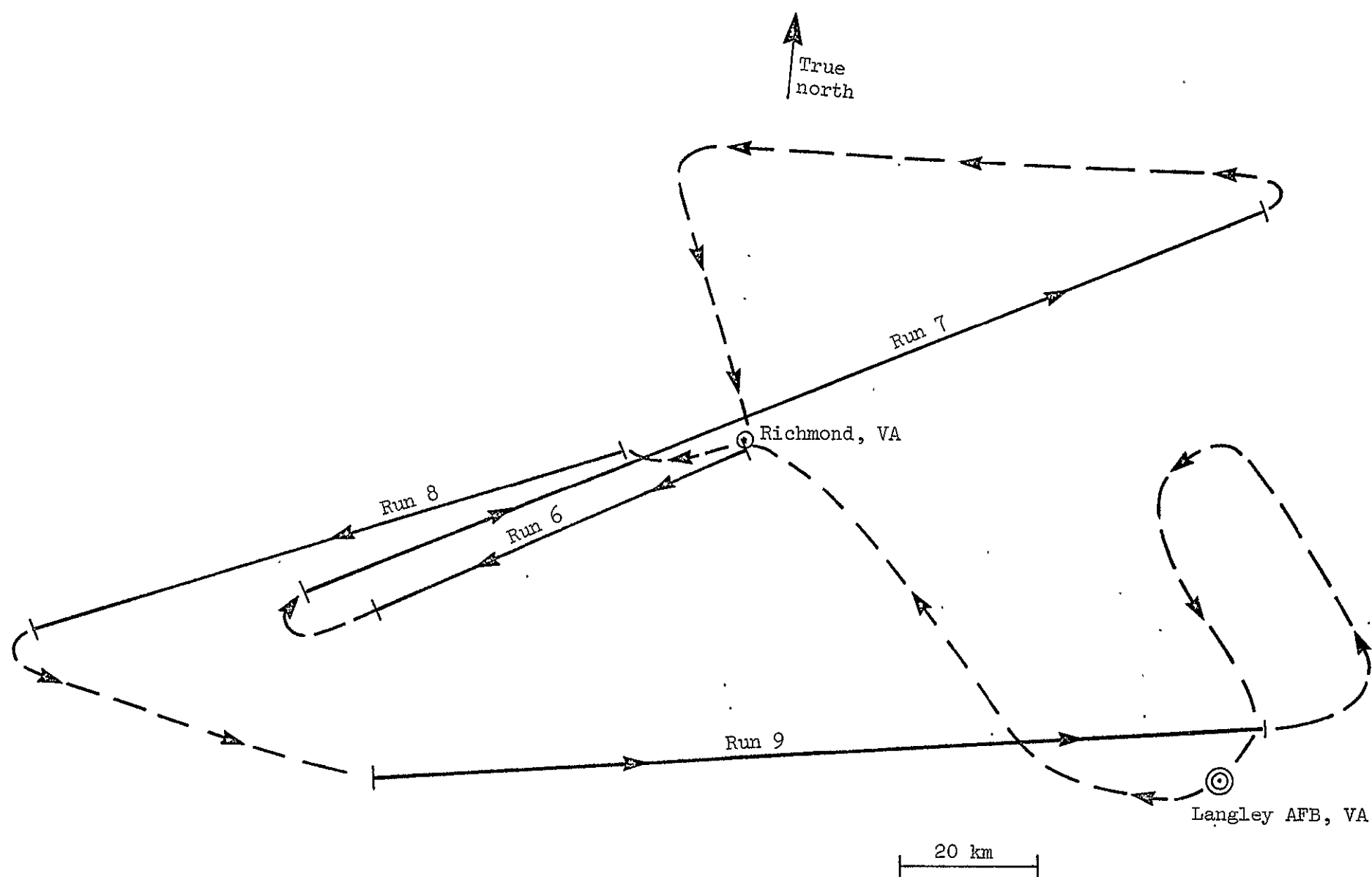


Figure C-18.- Track for Flight 24, 1612-1804 GMT, December 17, 1974. All runs at 5.9 km alt.

Meteorological Conditions

The flow over the mid-Atlantic states was weak within 1500 m of the surface at 1200 GMT. Two low pressure centers, both with 1000 mb central pressure, were located over the Great Lakes and coastal New England at 1800 GMT (fig. C-19). A high pressure area centered in southern Texas was moving eastward and pressures were rising over the southeast. Weak flow at low levels along the Atlantic coast was overlain by an intense jet stream. Winds at 500 mb (1200 GMT) were 62 m sec^{-1} at Cape Hatteras, NC (fig. C-20) and exceeded 75 m sec^{-1} in the core of the jet stream at several levels. The jet core, which appeared to be centered near 400 mb (fig. C-21) was located above and slightly to the west of the maximum winds at 500 mb, resulting in large vertical wind shears below the core. Significant shears were found at several stations along the Atlantic seaboard. Cape Hatteras, Wallops Station, and Washington, DC had vertical shears of at least $.029 \text{ sec}^{-1}$ near and slightly above the 500 mb level. Aircraft-measured winds obtained during climbout showed an increase in windspeed of 46 m sec^{-1} between 5 and 6.7 km altitude, corresponding to a shear of $.027 \text{ sec}^{-1}$. (Note on figure C-23 that the layer was nearly isothermal.) Horizontal shears were also quite large in this region. For example, the 1200 GMT 500 mb wind speed at Washington was 18 m sec^{-1} higher than at Wallops Station, located some 400 to to the southeast. Most of this change appears from the wind analysis to have occurred over only half the distance between the two stations. This resulted in a horizontal wind shear of around 5 m sec^{-1} in 75 km.

Surface pressures in the southeastern U.S. continued to rise during the 12 hours following 1200 GMT. The trough at 500 mb remained relatively

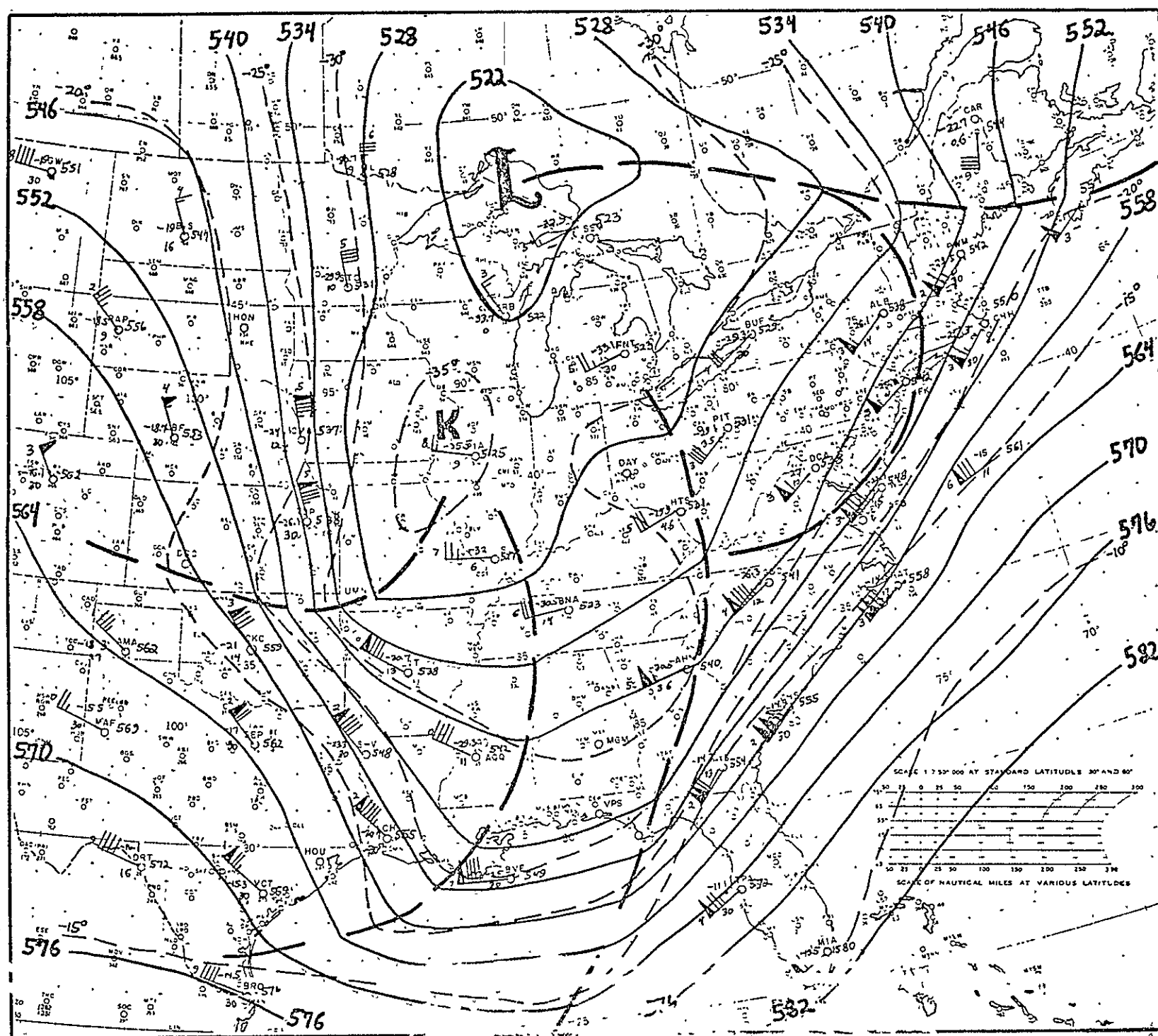


Figure C-20. - 500 mb Analysis, 1200GMT, December 17, 1974. . Heights in gpdam.

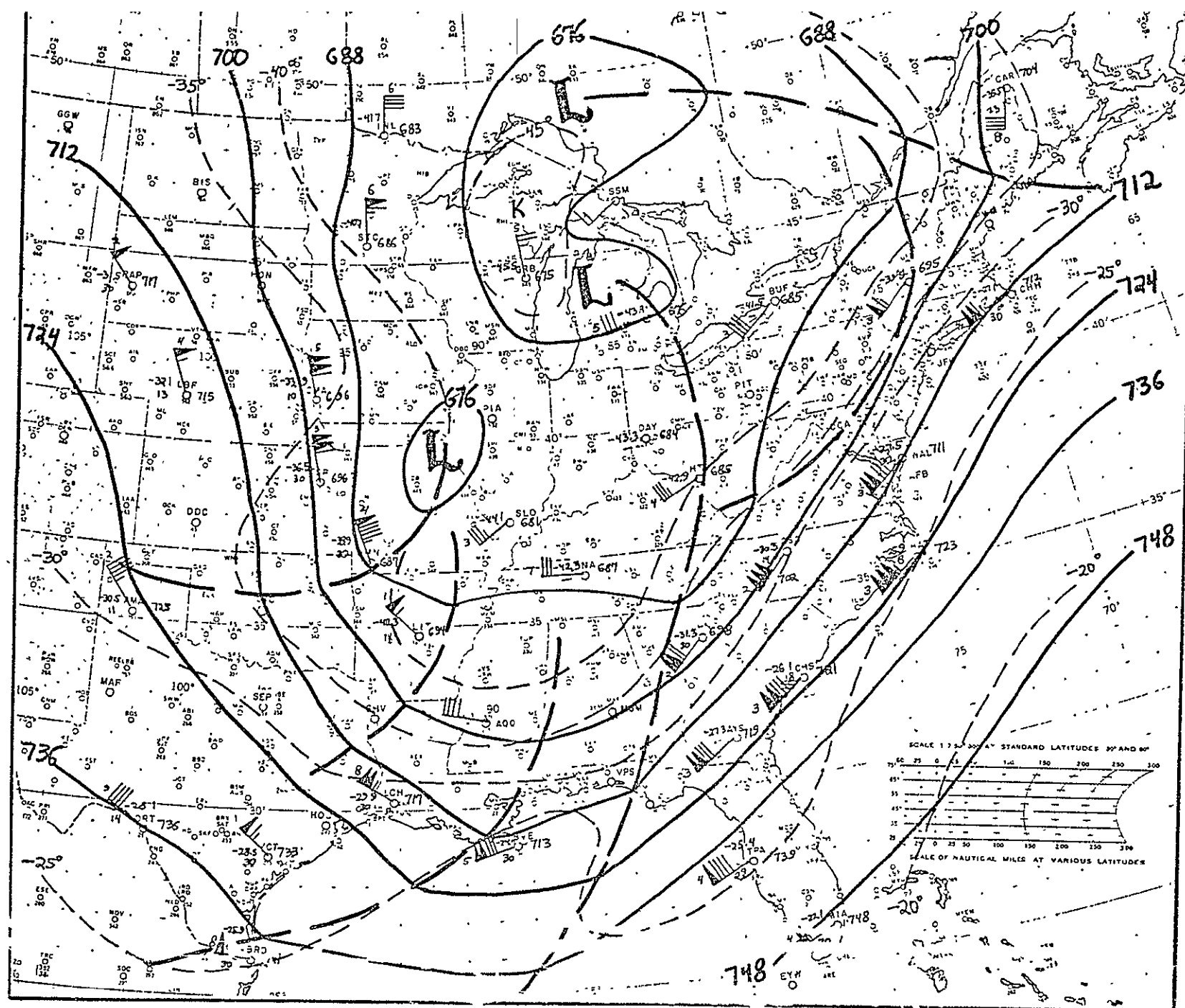


Figure C-21. - 400 mb Analysis, 1200GMT, December 17, 1974. Heights in gpdam.

stationary but broadened considerably during this period resulting in weaker wind speeds and small vertical wind shears in central North Carolina and Virginia. Wind speeds and directions at jet stream levels remained relatively unchanged during this 12 hour period along the central Atlantic coast, however. Vertical shears of $.019 \text{ sec}^{-1}$ and higher existed over layers several thousand feet thick at altitudes above 500 mb at both Cape Hatteras and Wallops Station.

The 1200 GMT horizontal temperature field at 500 mb showed a large east-west gradient extending from southeastern Virginia to Southwestern Georgia (fig. C-22). Data from special rawinsonde releases at Washington and Wallops Station, coinciding with the time of the B-57B flight, indicate that the gradient became somewhat stronger in the northern Virginia region after 1200 GMT as cold air was being advected into the Washington area (fig. C-23). B-57B climb and descent temperatures, also included in the figure, are representative of an area approximately 275 km to the south of Washington. Richardson numbers, computed from the special rawinsonde data, were near or below the critical value of 0.25 between 5.7 and 6.0 km at Wallops Station and between 6.5 and 6.6 km at Washington. Numerous commercial airline pilot reports of moderate turbulence were reported within these altitude bands in New Jersey and Delaware about 2 hours prior to the balloon releases. It is not known whether these encounters were within cirrus clouds. Extensive cirrus cloud cover was observed during the B-57B flight in eastern Virginia around the altitudes of the pilot reports.

Discussion

Only brief patches of light to light-moderate turbulence were found, despite a meteorological situation where large horizontal and vertical wind shears

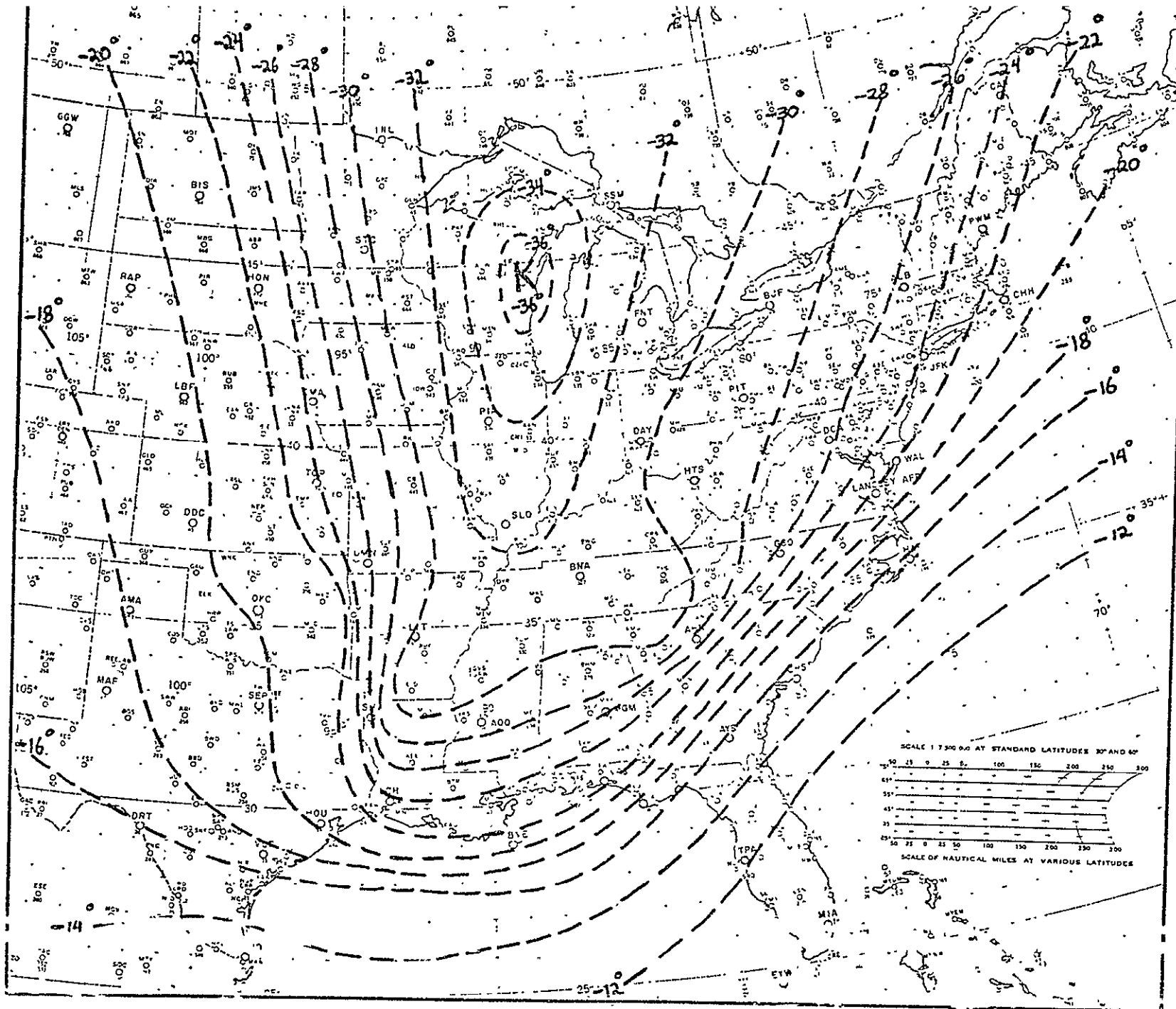


Figure C-22.- 500 mb Temperature Analysis, 1200 GMT, December 17, 1974
Temperatures in Degrees Celsius

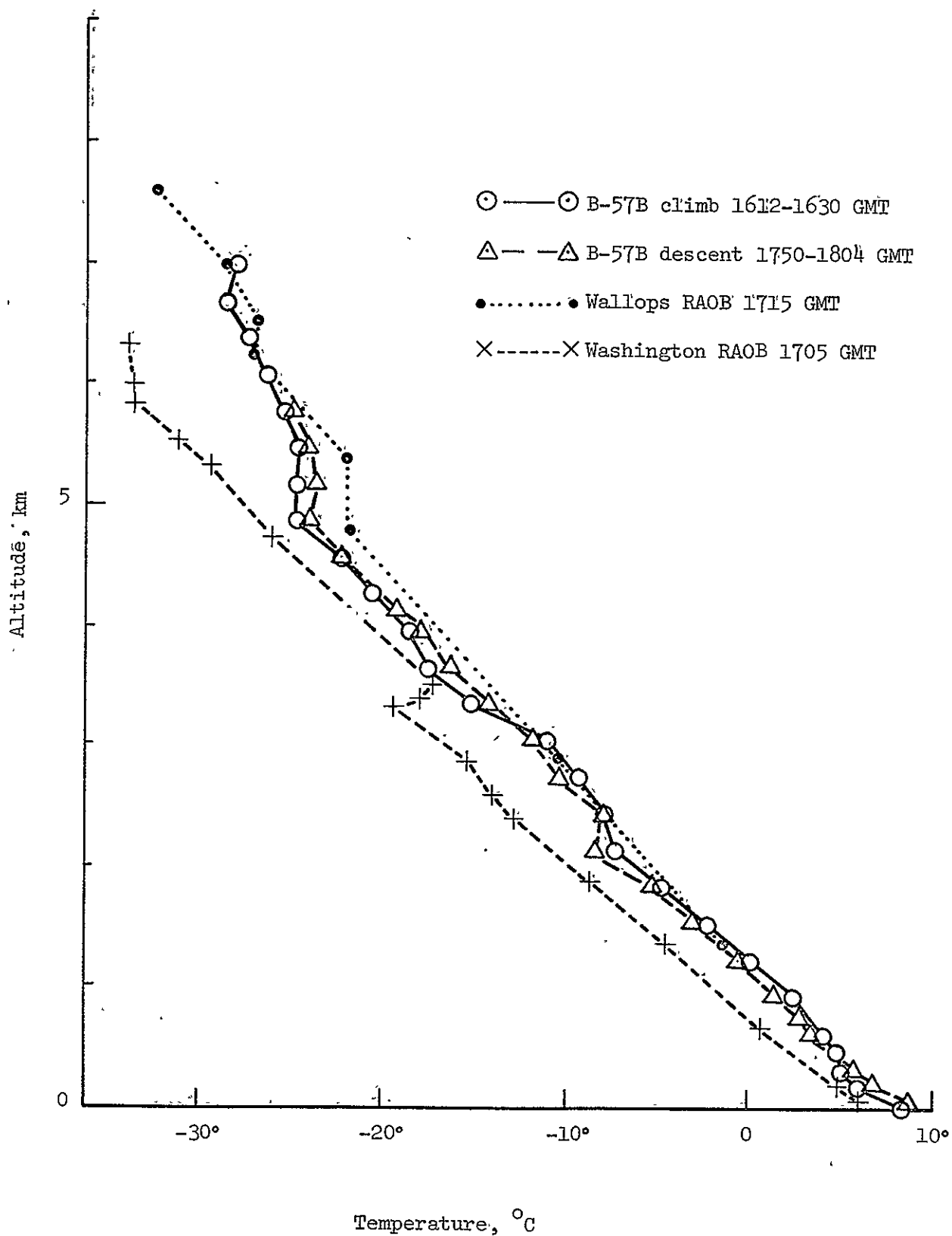


Figure C-23. - MAT B-57B, Washington, DC, and Wallops Island, VA temperature soundings for Flight 24, December 17, 1974

and low Richardson numbers existed near the flight area. Also there were numerous pilot reports of turbulence within close proximity in time and location to the B-57B flight. The turbulence sampled by the aircraft was generally associated with cirrostratus clouds. Meteorological data acquired subsequent to the flight indicated that the zone of maximum shears progressed eastward and that much of the sampling area was west and probably south of the most intense and continuous turbulence (as verified by the commercial and military pilot reports). The pilot reports did not contain information as to whether their encounters were in clouds. Failure of the B-57B to locate more turbulence was partly due to the inability of rawinsonde data to depict small scale horizontal features and their changes with time.

Flight 25, December 31, 1974, 1154 - 1340 EST (1654 - 1840 GMT)

Flight Summary

The flight was a turbulence search mission in the vicinity of a moderately strong vertical wind shear zone between Greensboro and Cape Hatteras, NC. The B-57B flew from 140 km southeast to 90 km northwest of Rocky Mount, NC between 11.9 and 12.5 km. Only very light, patchy turbulence was encountered at these altitudes with RMS meter readings (10 sec average) generally lying between 0.01 and 0.03. Consequently, no records were taken. On the climbout light turbulence occurred at 3.0 km and light-moderate turbulence at 5.2 km within clouds. Light CAT was encountered on descent at 6.7 km and light moderate turbulence in clouds at 3.8 km. No turbulence was noted while transversing between 9.8 and 10.7 km, an altitude layer where large wind shears were reported on the 1200 GMT RAOBs (rawinsonde observation) at the two North Carolina stations.

Meteorological Conditions

Surface weather at 1200 GMT along the mid-Atlantic states was dominated by a large high centered off the New Jersey coast. Pressures were falling rapidly, however, and precipitation moving eastward reached the Langley AFB area by flight-time. Upper level flow over the surface high was slightly anticyclonic. The jet core was located in the New York-New England region where winds exceeded 75 m sec^{-1} at 10.7 km. Strong flow extended well out from the core, with 50 m sec^{-1} winds as far south as North Carolina. Vertical wind shears of $.020$ to $.024 \text{ sec}^{-1}$ were noted on both the Greensboro

and Cape Hatteras 1200 GMT RAOBS near 10.1 km and 11.9 km. The lower shear layer had a Richardson number of 0.2 and the upper layer 0.7. No pilot reports of turbulence were noted at these altitudes within several hundred km of the search area.

Discussion

The B-57B encountered smooth air in an altitude band which was characterized by Richardson numbers below the critical value of 0.25. This layer, only briefly traversed, was in an area northeast of the line between Greensboro and Cape Hatteras. Although negative wind shears in the upper layer near 11.9 km were as large as the shears at 10.1 km, stability in the upper layer was greater and Richardson numbers were above the critical value. The flight also took place several hours after the rawinsonde releases when the synoptic situation near the surface was changing rapidly. The patchy, low intensity turbulence that did exist has been observed on several other MAT flights within moderately strong shear zones.

Flight 26, January 14, 1975, 1212-1446 EST (1712-1946 GMT)

Flight Summary

Perusal of rawinsonde data taken before the mission revealed that large vertical wind shears existed over stations to the south and west of Virginia. The B-57B was ~~dispatched to Greensboro, NC~~ one hour after a NASA T-38 turbulence probe aircraft indeed reported that moderate turbulence was present in that area between 9.1 and 9.5 km. The T-38 also found several areas of light-moderate turbulence along the North Carolina coast and southeast of Greensboro at 7.9 and 10.7 km. Five data runs were made between 9.0 and 9.6 km in an area extending from Greensboro to Richmond, VA (fig. C-24). Very light turbulence was recorded on runs 6 and 8, the lowest and highest runs made in the search area. Light to light-moderate and occasionally moderate turbulence was encountered on runs 5, 9, and 10 which were 45 to 180 km in length and located between 9.1 and 9.5 km. Other pilot reports of moderate turbulence on the 14th included an early morning encounter between 10.4 and 11.6 km by a C-141 near Dover, DE and several reports between 9.5 and 12.8 km over northwest Georgia near the time of the B-57B flight.

Meteorological Conditions

(a) Synoptic Pattern.- An extensive high pressure cell covered most of the eastern U.S. at 1800 GMT (fig. C-25). Northwest winds of 5 to 8 m sec⁻¹ at the surface existed in the Virginia area from flow around the high. The 500 mb map at 1200 GMT (fig. C-26) shows that an extensive trough was centered south of the Great Lakes with moderately sharp curvature in the flow along a line from central North Carolina to Virginia. Largest wind

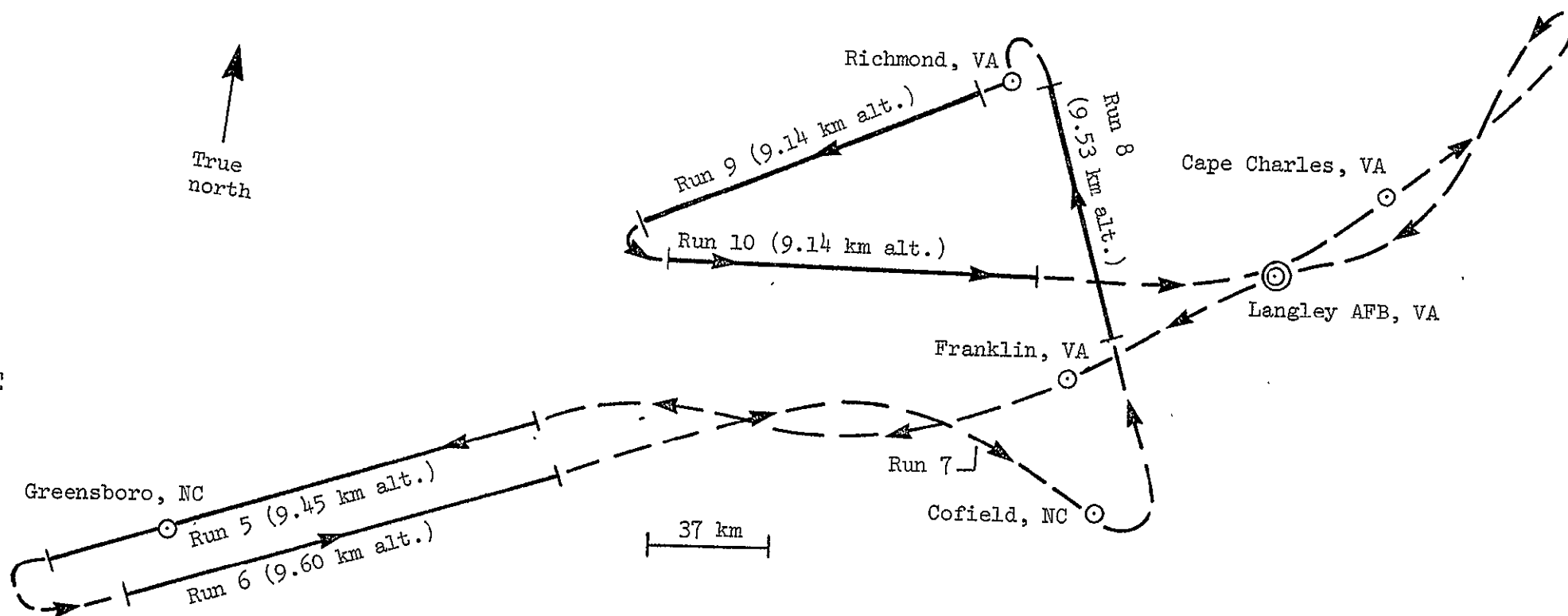


Figure C-24.- Track for Flight 26, 1712-1946 GMT, January 14, 1975.

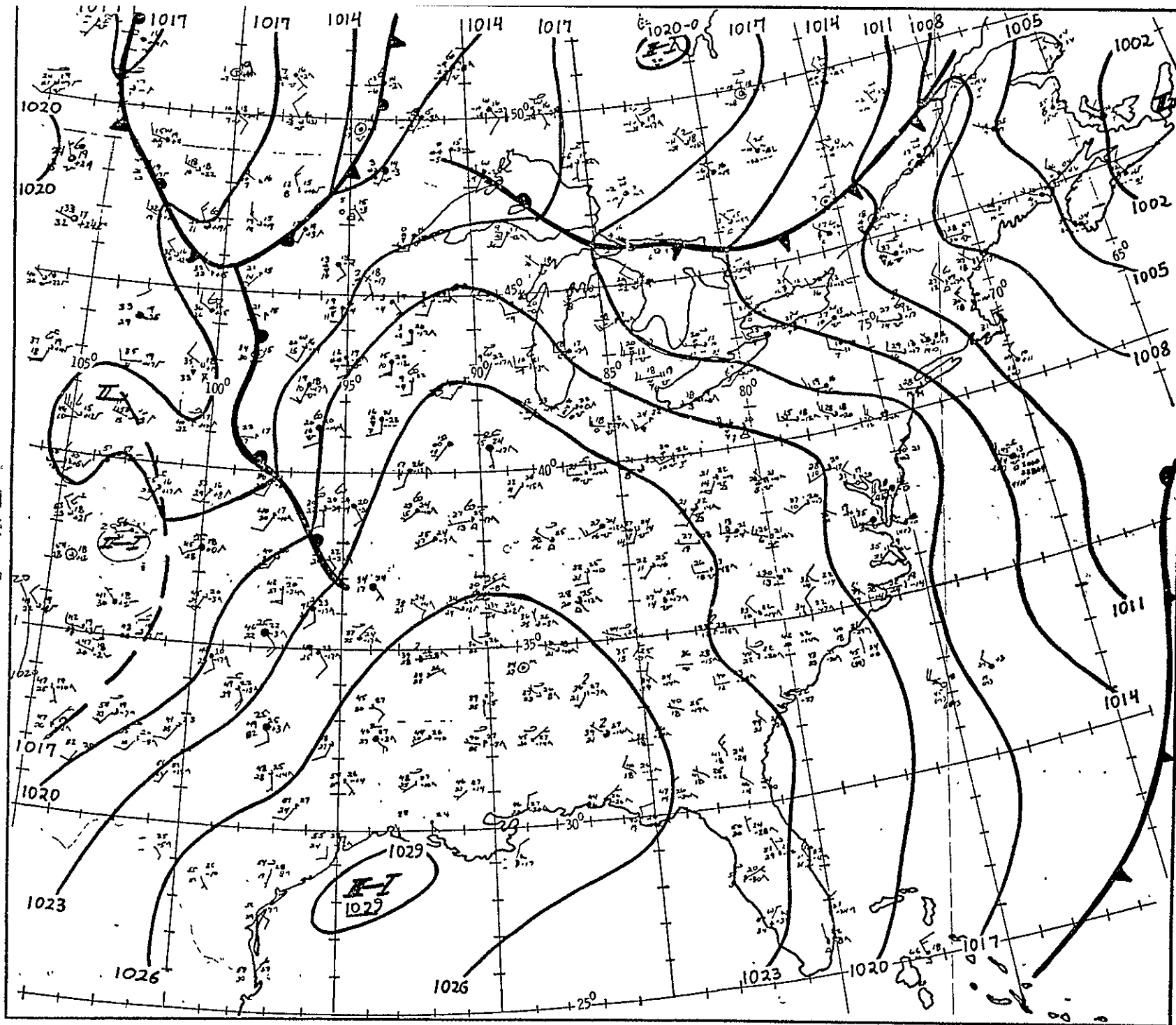


Figure C-25. - Surface Analysis, 1800GMT, January 14, 1975. Pressures in mb.

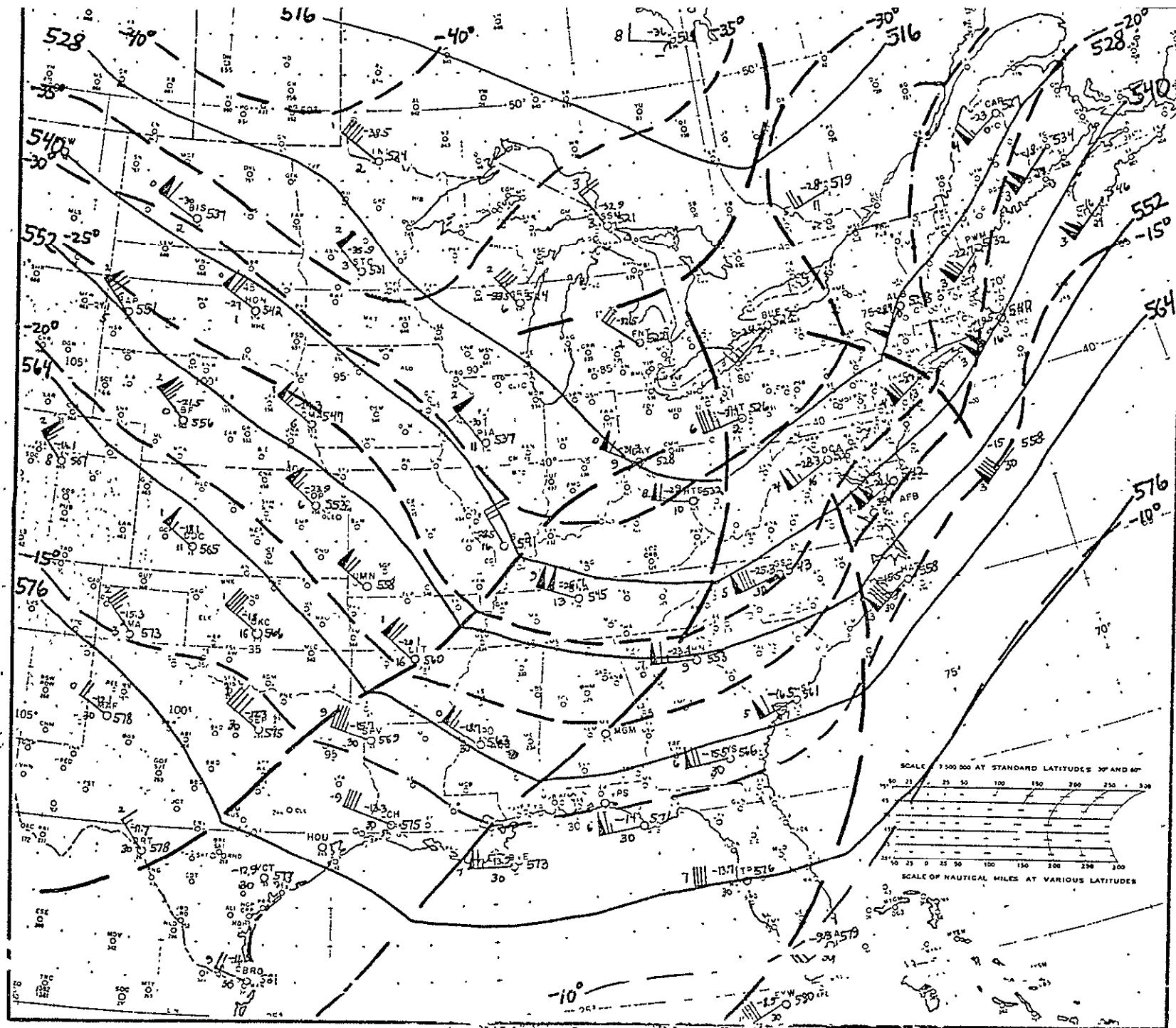
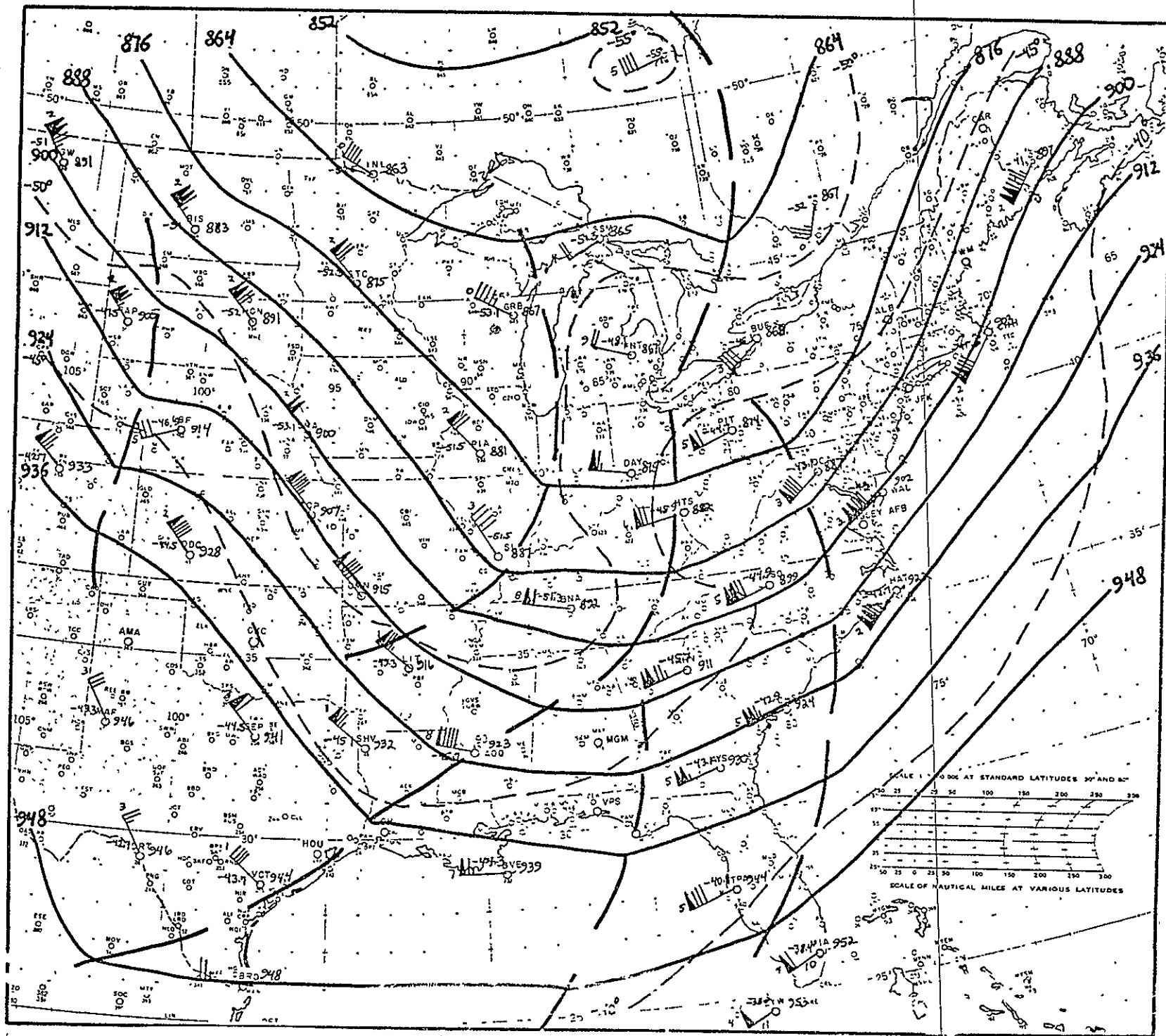


Figure C-26. - 500 mb Analysis, 1200GMT, January 14, 1975. Heights in gpdam.



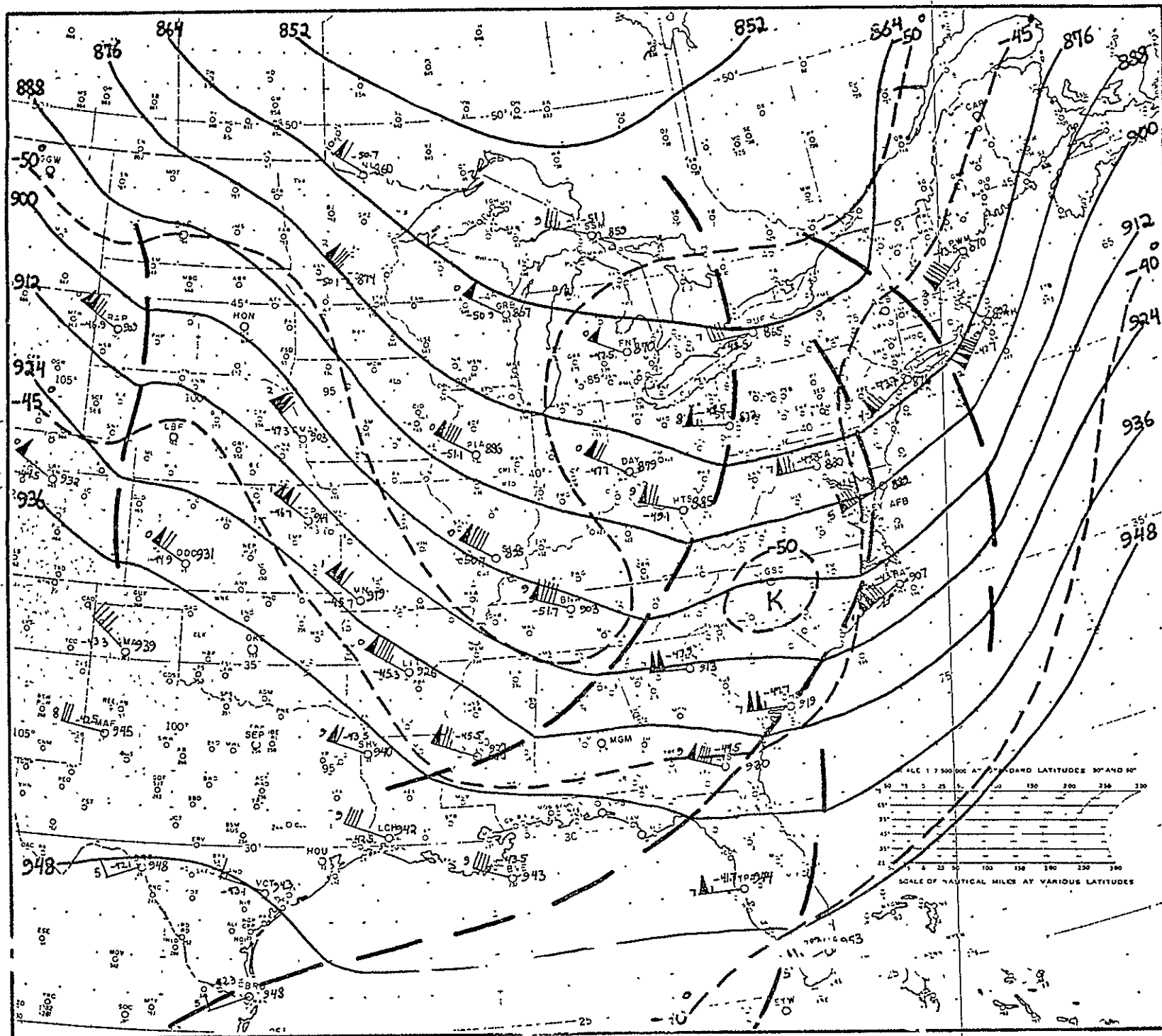


Figure C-29. - 300 mb Analysis, 0000GMT, January 15, 1975. Heights in gpdam.

speeds were in eastern North Carolina and Virginia, in excess of 50 m sec^{-1} . Jet stream winds, located near 300 mb, were as high as 77 m sec^{-1} in the same region (fig. C-27). The zone directly west of the jet stream had pronounced horizontal wind shears. For example, the 300 mb wind at Washington was $225^\circ/46 \text{ m sec}^{-1}$ compared to $235^\circ/72 \text{ m sec}^{-1}$ at Wallops Station.

The trough at 500 mb had broadened somewhat by 0000 GMT on the 15th which reduced the directional change in the horizontal flow considerably (fig. C-28). The main jet axis was farther east than 12 hours previously and located offshore in the Virginia area, which resulted in the winds being more westerly at 300 mb over North Carolina (fig. C-29).

(b) Rawinsonde and B-57B Sounding Data.— There were several stations in the southeastern U.S. with soundings having vertical wind shears of $.022 \text{ sec}^{-1}$ or greater at 1200 GMT. Nashville, TN winds changed from $265^\circ/27 \text{ m sec}^{-1}$ to $285^\circ/39 \text{ m sec}^{-1}$ between 9.5 and 9.8 km. Athens, GA had a negative shear of $.037 \text{ sec}^{-1}$ above 9.5 km and Washington $-.024 \text{ sec}^{-1}$ above 10.7 km. No wind data existed above 8.8 km at Greensboro. With the expected eastward movement of the upper air trough, it was anticipated that the vertical shear zone observed at Nashville would progress into North Carolina by the time scheduled for the B-57B flight.

Special rawinsonde releases were made at Greensboro and Wallops Station about 1 to 1-1/2 hours after the B-57B flight. Vertical wind shears in the layer coinciding with the B-57B search altitude were only $-.013 \text{ sec}^{-1}$ at Greensboro but were $.025 \text{ sec}^{-1}$ at Wallops Station, possibly indicating an accelerated movement of the shear zone northeastward. Temperature data from the Greensboro 1200 GMT sounding and special balloon release at 2125 GMT (1625 EST) have been compared to the B-57B climbout temperatures in

figure C-30. The B-57B data was taken from 215 to 340 km east-northeast of Greensboro at around 1720 GMT. Cold air advection associated with movement of the trough was apparent at Greensboro above 6.1 km. Temperature differences between Greensboro and the areas to the east appear to have been maximum at the level where the turbulence occurred. However, only 1°C to 2°C trends were noted on the data runs.

Aircraft wind data for the B-57B climbout are also plotted in figure C-30. The Richardson number, (Ri) computed from these data and climbout temperatures, were found to be below the critical value in a narrow layer centered at 8.8 km. Only a few very light bumps were noted near this altitude on climbout. Wind speeds in the layer were near 67 m sec^{-1} or about 15 to 26 m sec^{-1} higher than in the turbulent region. A vertical wind shear of $.046 \text{ sec}^{-1}$ and a Ri of .09 were calculated for a section of run 9 where the B-57B both climbed and descended 250 m. The run contained 60 km of light and occasionally moderate turbulence. A wind speed increase of 30 m sec^{-1} and a directional shift of 30° (from west to west-southwest) was noted in traversing the search area during the data runs.

Discussion

The area of light to moderate turbulence traversed by the B-57B appears to have been related to moderate curvature in the wind direction, large horizontal wind shears located along a temperature frontal zone west of the jet stream, and low Ri resulting from large vertical wind shears. Although the turbulence encountered by the B-57B lay primarily

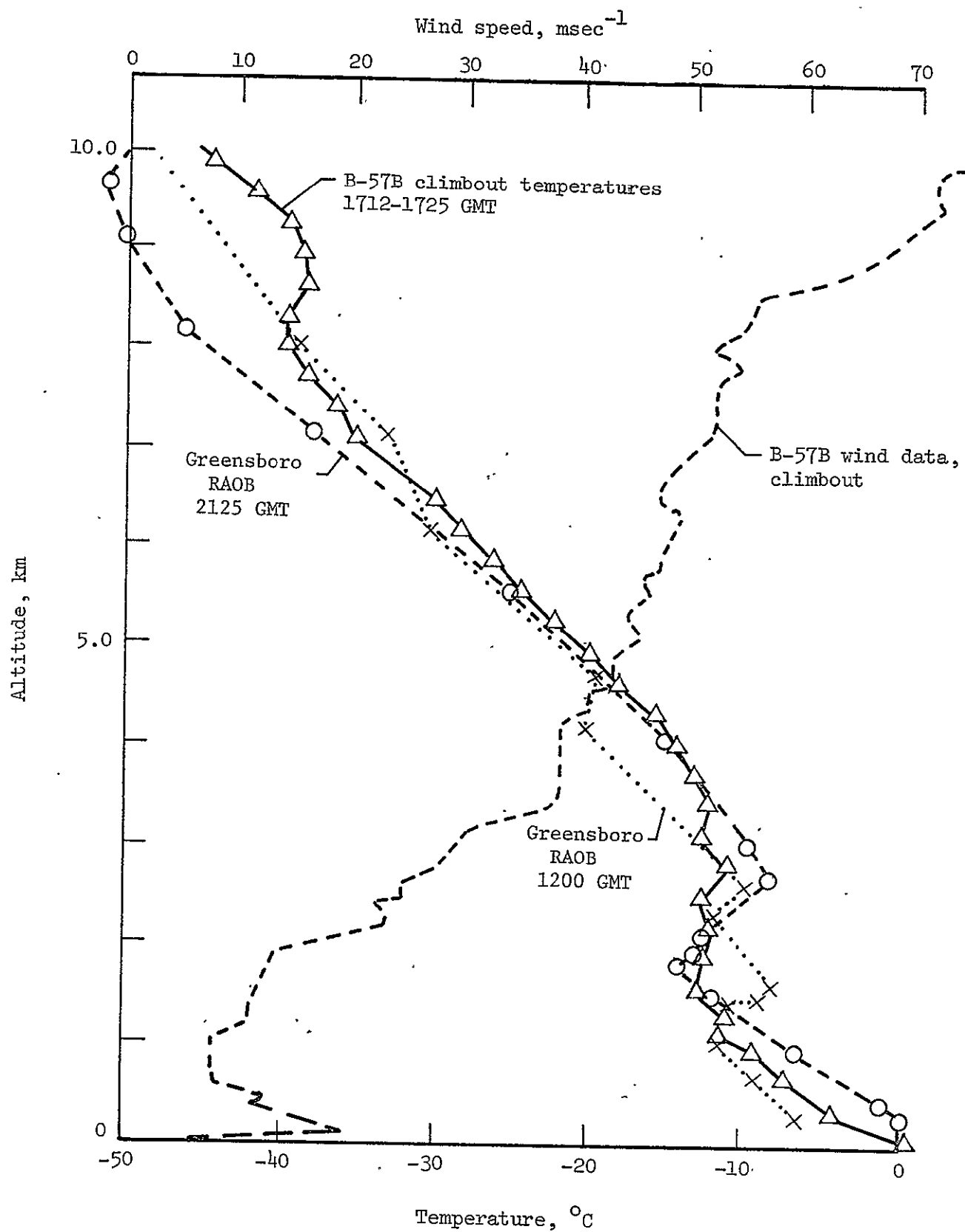


Figure C-30.- MAT B-57B and Greensboro, NC temperature soundings for Flight 26, January 14, 1975.

within a 300 m thick altitude band, NASA and commercial aircraft reports indicated that there were several areas and altitudes with moderate turbulence along the eastern seaboard. The turbulence appeared to have been concentrated along a roughly north-south line, and apparently moved eastward at a rapid rate.

Flight 27, January 30, 1975, 1048-1307 EST (1548-1807 GMT).

Flight Summary

This was the final flight in the first phase of the MAT program conducted from the NASA Langley Research Center. The purpose of the flight was to search for turbulence associated with a jet stream core located near New York City and for wind shear turbulence below 5.5 km altitude south of New York. The flight proceeded north-northeastward from Langley AFB at 10.7 km where two runs (10 and 13) were made, one heading northward from a point 74 km south-southeast to a point 55 km northeast of New York City and the other on a reciprocal heading from 18 km south to 165 km south-southeast of the city. Only very light chop interspersed with several smooth areas was encountered on both runs. Some searching was done near New York City in thin cirrus clouds at 11.1 km but conditions were smooth. On return to Langley AFB the B-57B descended to 4.7 km where light turbulence was encountered near Wallops Station below an altostratus cloud deck (fig. C-31). The cloud was 300m thick and extended from north-northwest to south-southeast. Run 17 was made parallel to and about 200 meters below the cloud, paralleling its long dimension. Continuous light turbulence, lasting for nearly 180 km, was experienced. After a 180° turn to a north-northeast direction continuous light turbulence was again encountered on run 18 at 4.8 km. The intensity of the turbulence did not appear to change during periods when the aircraft entered the bottom of the clouds. Only a scattering of pilot reports, mostly of light chop below 6 km, were received on this date in the northeastern U.S.

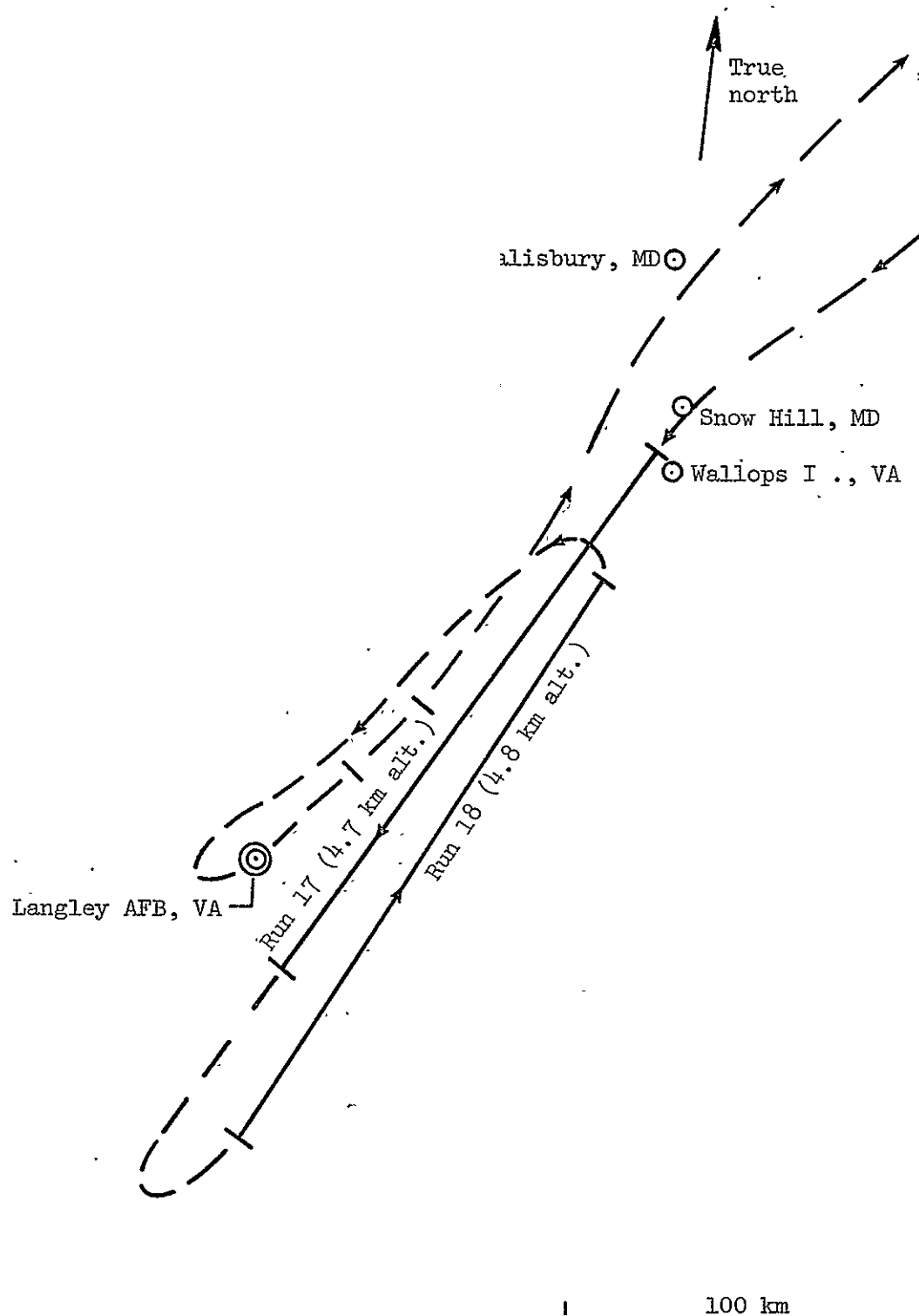


Figure C-31.- Low altitude track for Flight 27, 1548-1807GMT, January 30, 1975.

Meteorological Conditions

(a) Synoptic Data.- An intense low pressure system had rapidly moved across the northeastern U.S. on the 29th and at 1800 GMT was located several hundred miles northeast of Maine. High pressure covered most of the upper midwestern and central Atlantic states (fig. C-32). Nearly zonal flow was characteristic of the upper levels from Virginia northward with winds in excess of 50 m sec^{-1} existing throughout a deep layer. Slight convergence appeared on the 1200 GMT map for 500 mb along the Atlantic coast (fig. C-33). The jet stream, centered near 250 mb (fig. C-34), was quite broad with winds 62 m sec^{-1} or greater across several hundred km of its width and at least 77 m sec^{-1} along the core from the Rockies to the Atlantic. The large depth of the jet stream on this date can be seen from New York City's winds which were in excess of 50 m sec^{-1} from 5.2 to 15.2 km with a maximum of 85 m sec^{-1} occurring at 10.4 km. Winds measured on runs 10 and 13 over New York City averaged 82 m sec^{-1} , from 290 degrees. Broadness of the jet and lack of curvature in the flow reduced the probability of turbulence, however. There were no appreciable changes in the upper level flow at either 500 mb or 250 mb from 1200 GMT on the 30th to 0000 GMT on the 31st.

(b) Sounding and aircraft data.- Vertical wind shears of appreciable magnitude were generally absent near the flight location in the positive shear zone just below the jet stream, except over Washington, DC, where the wind shear was $.027 \text{ sec}^{-1}$ from 10.1 to 10.7 km. Above the jet several stations along the eastern seaboard had shears of $.017 \text{ sec}^{-1}$ ($16.9 \text{ m sec}^{-1} \text{ km}^{-1}$) or greater. In the layer between 4.6 and 4.9 km, which coincided

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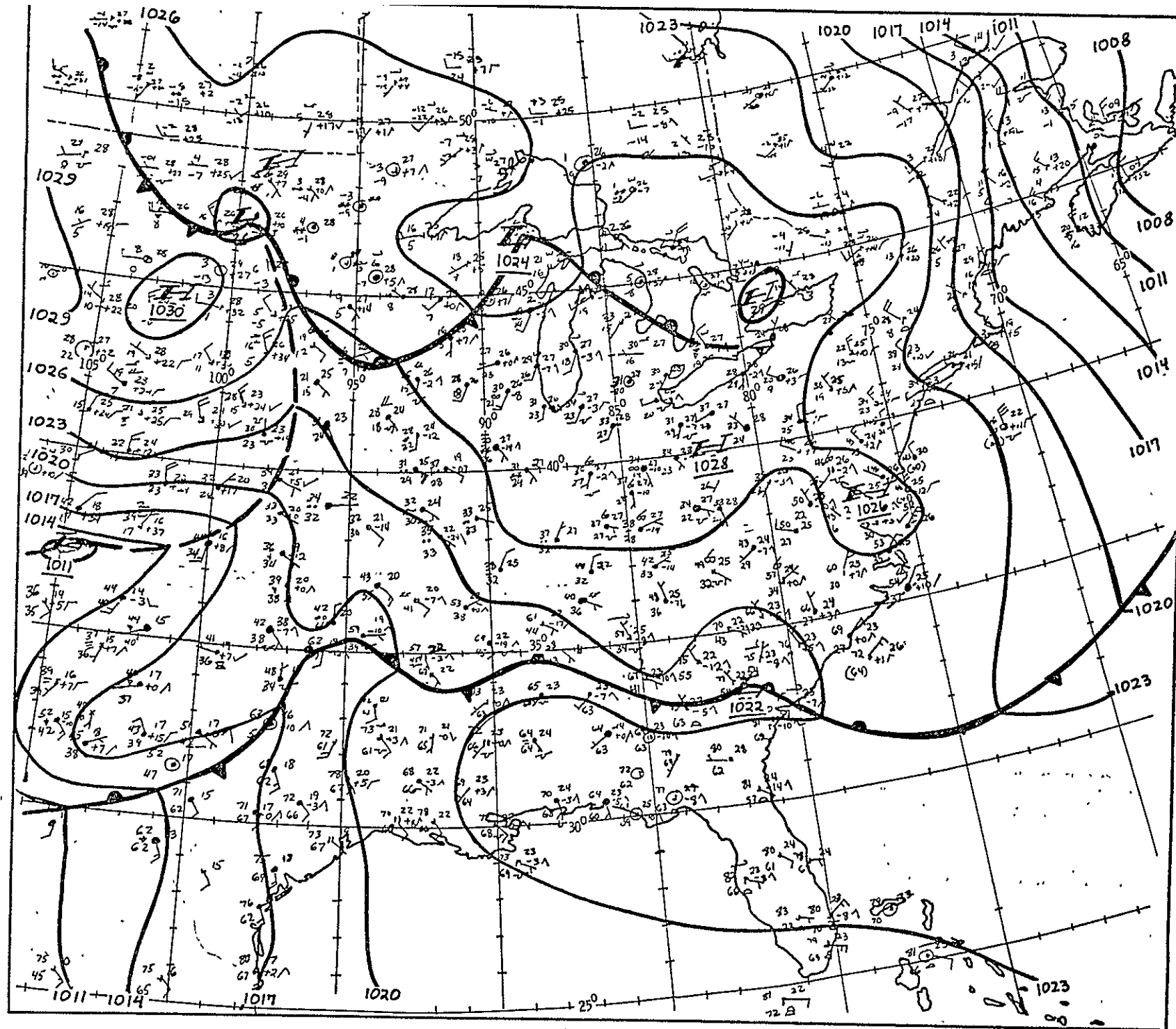


Figure C-32. - Surface Analysis, 1800GMT, January 30, 1975. Pressures in mb.

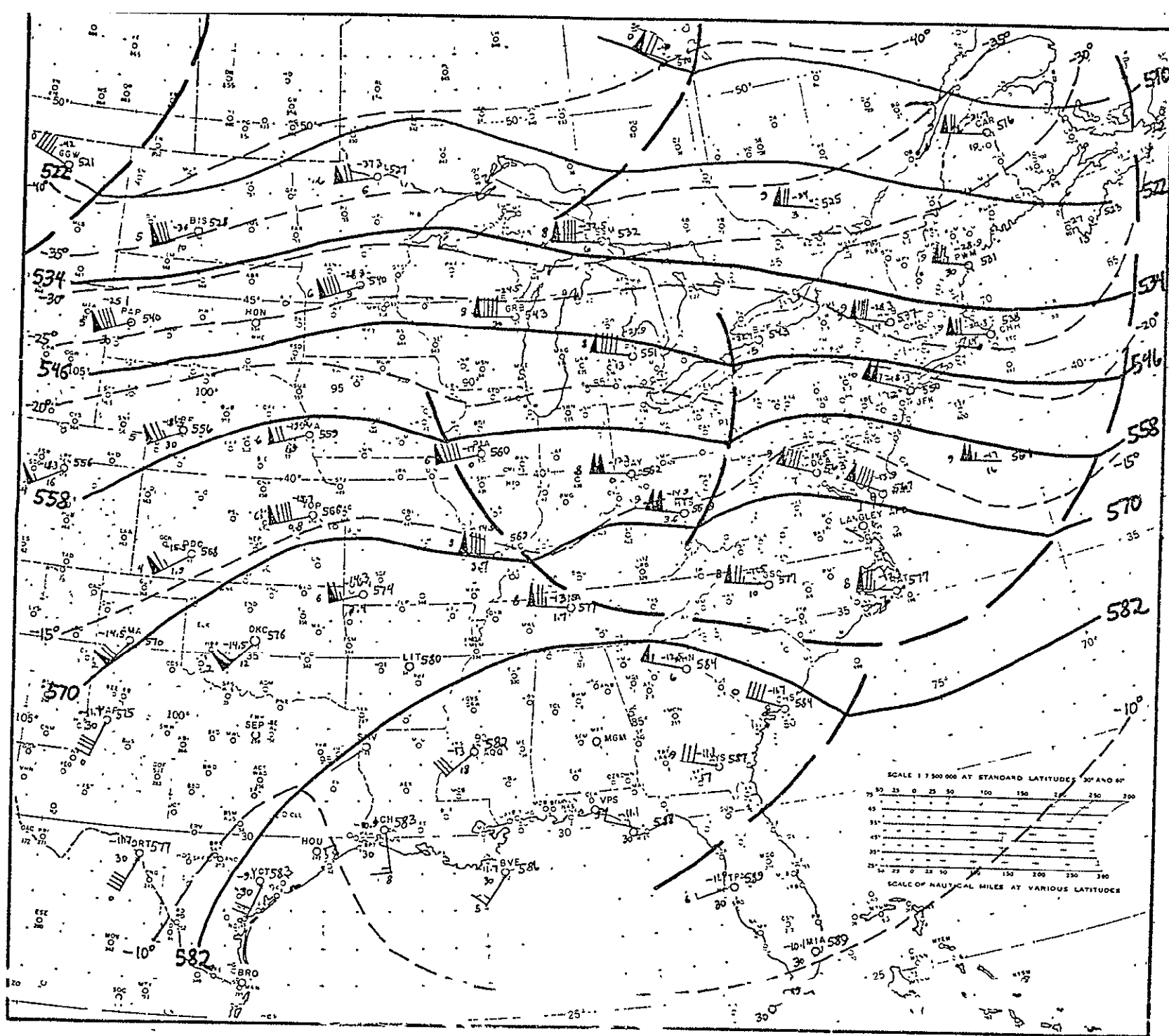
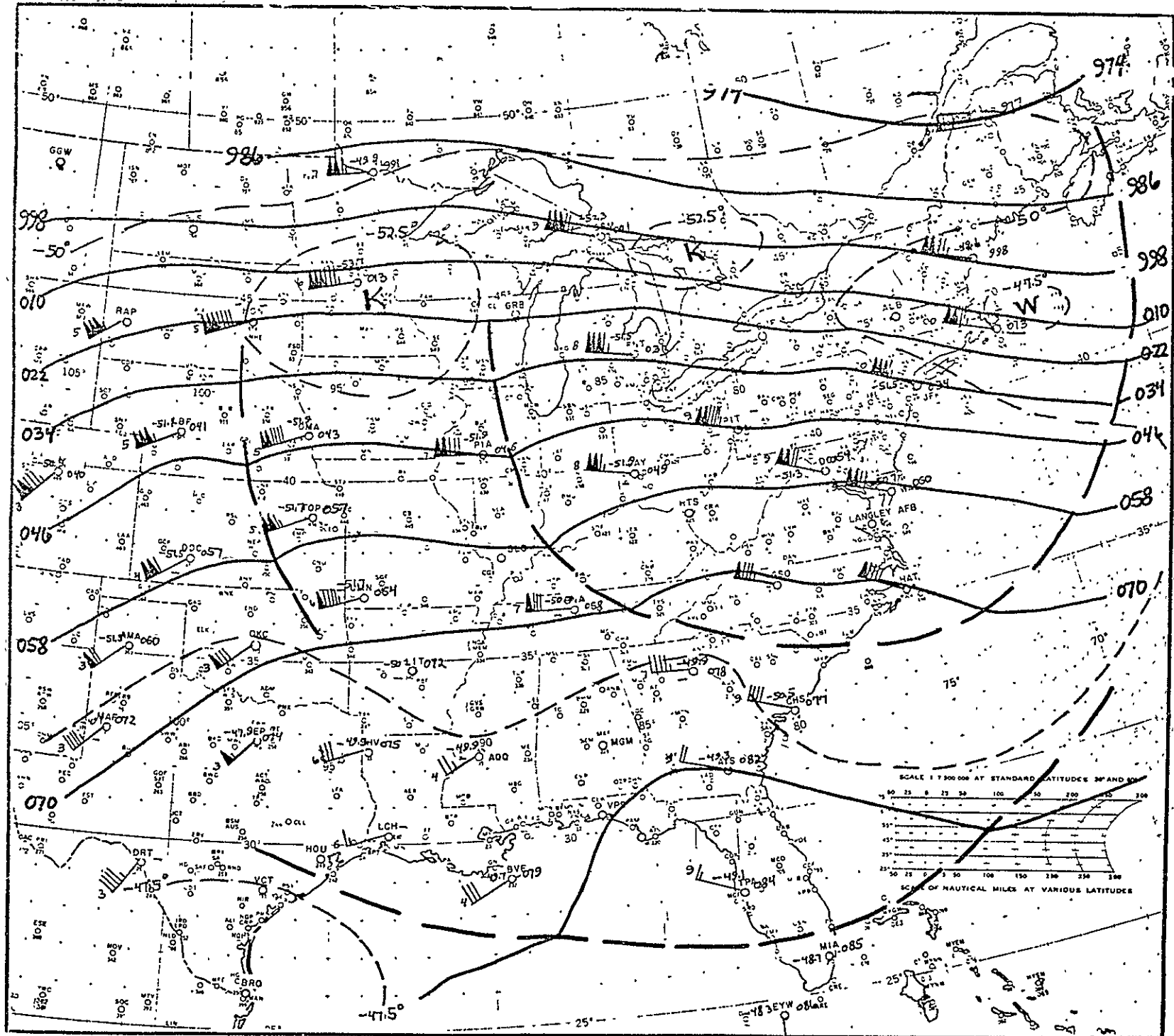


Figure C-33. - 500 mb Analysis, 1200GMT, January 30, 1975. Heights in gpdam.



with the turbulence, the vertical wind shear at Wallops Station, calculated from the 1200 GMT rawinsonde data, was only $.007 \text{ sec}^{-1}$. The balloon release, however, occurred approximately 5 hours before the flight and the meteorological situation was changing rapidly during the interim period. The shear in the same layer at Washington, located upwind from Wallops Station, was $.022 \text{ sec}^{-1}$ and the Richardson number was a low 0.28. A 4°C horizontal temperature decrease in 5 km was recorded on run 17 southeast of Langley AFB and a comparable increase was noted in the same location on run 18. Horizontal wind shears in this area were very small. The layer of altostratus clouds associated with the turbulence at 4.7 km probably formed just prior to the B-57B's encounter with the turbulence, as it was not visible on the climbout. The clouds appeared to be changing rapidly, being flatter on the top on run 17 and thicker with a smoother underside on run 18. Cloud bases were slightly lower on the southern end of the layer. Several layers of thin, hazy cirrus clouds were noted near New York City above 11.0 km. Some were brown in color, apparently containing a high density of pollutants.

Discussion

The extended zone of turbulence at 4.7 km appears to have been associated with vertical wind shear and low Richardson numbers below the jet stream. Altostratus clouds found in proximity to the turbulence were probably not directly related to the turbulence formation but may have enhanced the vertical motion in the layer adjacent to their bases. Rapidly changing cloud conditions suggest that the shear layer may have been part of a fast moving short wave trough. The considerably smaller shear near

the jet core decreased the probability of turbulence formation above the lower shear layer. An altitude band containing large negative shears above the jet was not investigated, because of limited fuel.

Flight 28, February 14, 1975, 1322-1531 PST (2122-2331 GMT)

Flight Summary

This flight was the first in the second phase of the MAT program, which was conducted from the NASA Dryden Flight Research Center. The flight plan called for searching to the east of the Sierra Nevada ridge where only a slight probability of mountain wave turbulence was expected, then for descending below 3 km to the lee of the Tehachapi mountains and sampling low altitude mechanical and orographic turbulence. Continuing high surface winds assured that turbulence would be found near the ground in this area.

The region east of the Sierra around Lone Pine, CA was searched up to an altitude of 12.5 km. A few patches of very light turbulence occurring mostly between 7.6 and 7.9 km and one short patch of light turbulence at 12.2 km were encountered. Four data runs were taken between 1.2 and 2.6 km over the Antelope Valley and Mojave Desert (fig. C-35). The elevation of the terrain below the aircraft on these runs was generally around 750 m but increased to 1050 m on the western edge. Run 4, heading east from Palmdale at 1.6 km, had turbulence ranging in intensity from very light to moderate-severe. The turbulence was orographically generated, generally decreasing with distance from the main ridges, but occasionally increasing again near isolated hills. Run 6 was just south of run 4 at 1.9 km. Turbulence was generally light to moderate in the first 64 km but decreased to only occasional very light patches in the final 28 km. Run 7 sampled orographic turbulence at 2.6 km altitude at a distance of 28 to 55 km from the Tehachapi range. Turbulence varied considerably in intensity, ranging from very light to moderate. The final leg, run 8, was at 1.3 km, starting

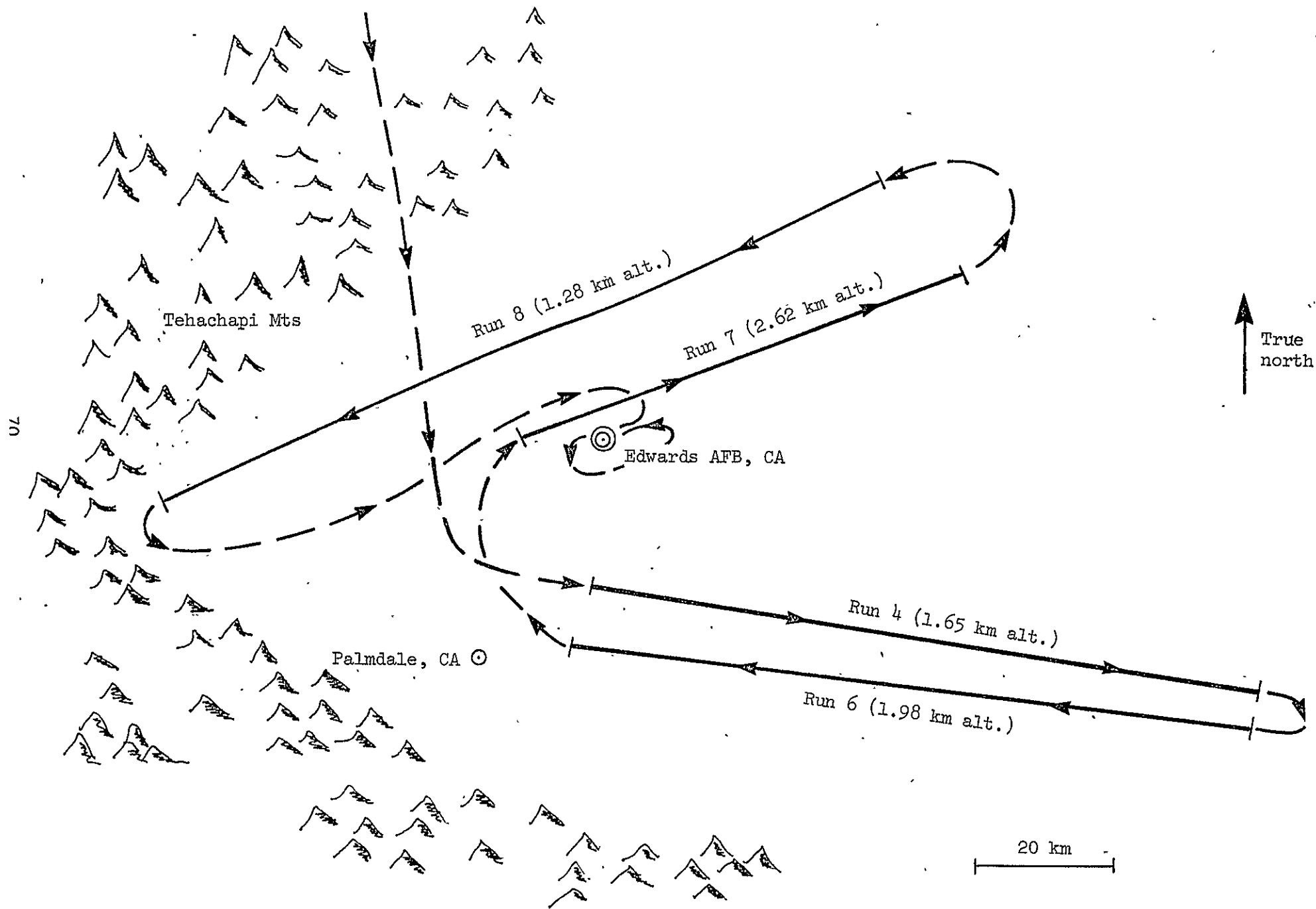


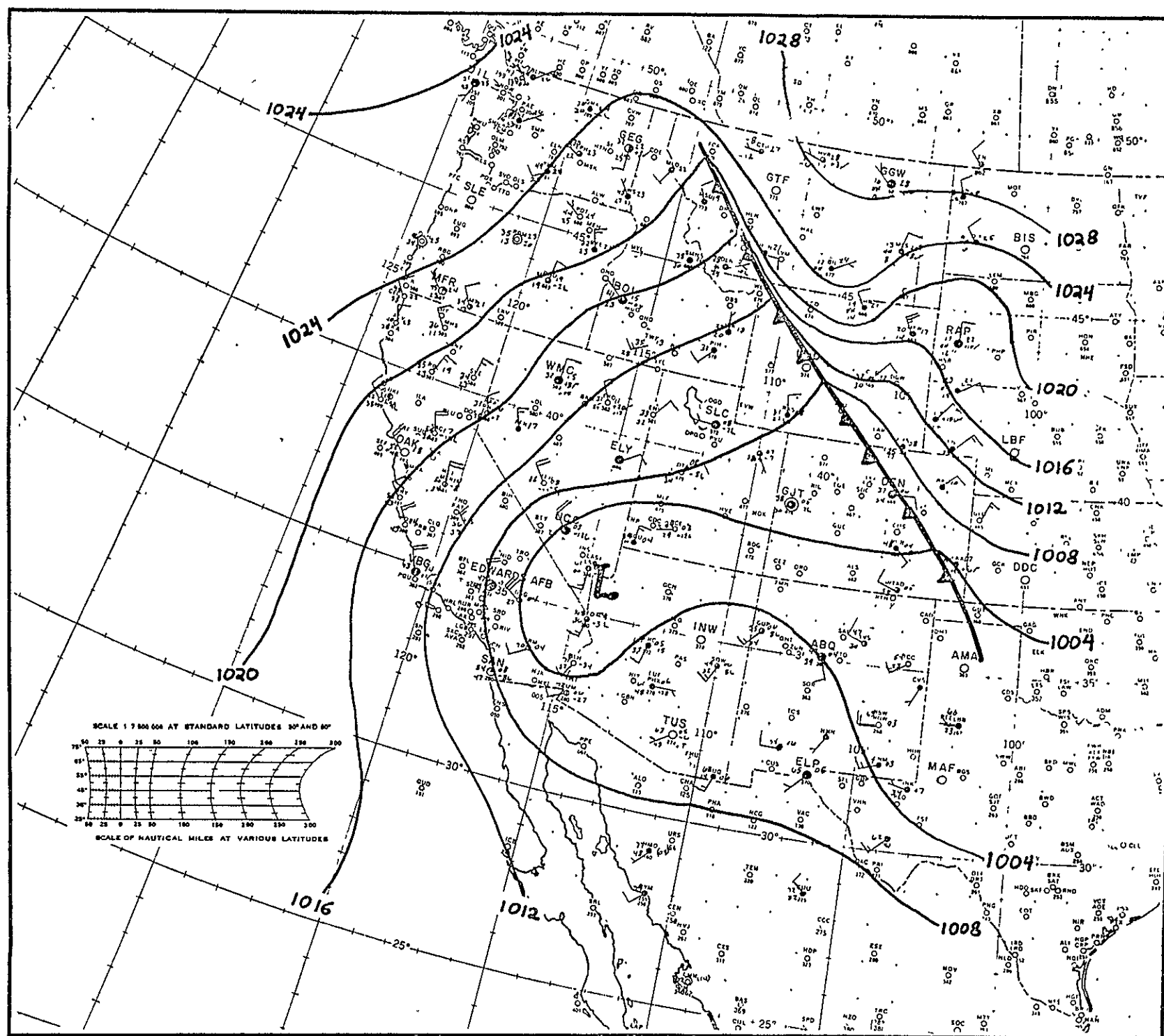
Figure C-35.- Southern track for Flight 28, 2122-2331 GMT, February 14, 1975.

at 37 km to the lee of the Tehachapis. The final 46 km of the run was in the rotor zone only 9 km to the lee of the mountain bases. Turbulence was continuous but variable in intensity (light to moderate) until entering the rotor zone where it was steady and severe.

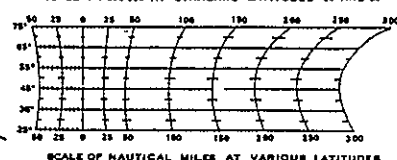
Meteorological Conditions

(a) Synoptic Situation.- The surface map showed a weak low in southern Utah at 1200 GMT with high pressure centered off the northern California coast. The resulting pressure gradient in central California produced surface winds of 5 to 10 m sec⁻¹ from the west-northwest in the desert area around Edwards AFB. At 850 mb the flow around a low in southern Nevada generated northwesterly winds of 10 to 15 m sec⁻¹ above flat terrain in central and southern California and much stronger winds in localized mountain areas. A trough was centered along the Pacific Coast states at 500 mb. The trough amplitude was greater over Washington and Oregon than over California. The jet maximum was at 11 km with winds averaging 36 to 46 m sec⁻¹ from the west-northwest in central California. This is not a favorable direction for Sierra wave formation.

Wind gusts of 18 m sec⁻¹ were reported at Edwards AFB during the B-57B takeoff. The surface pressure gradient had tightened considerably in southern California by 0000 GMT on February 15 (fig. C-36), which was only 1/2 hour after the B-57B landing. The low over Utah deepened and was now centered in northwest Arizona. The gradient also tightened at 850 mb as the flow underwent major changes in the 12 hours following 1200 GMT (fig. C-37). Pressures fell considerably in southern California and the low center moved from southern Nevada to Colorado. A deepening of the 500 mb trough, now centered along the Nevada-Utah border (figure C-38),



SCALE 1:750,000 AT STANDARD LATITUDES 30° AND 60°



SCALE OF NAUTICAL MILES AT VARIOUS LATITUDES

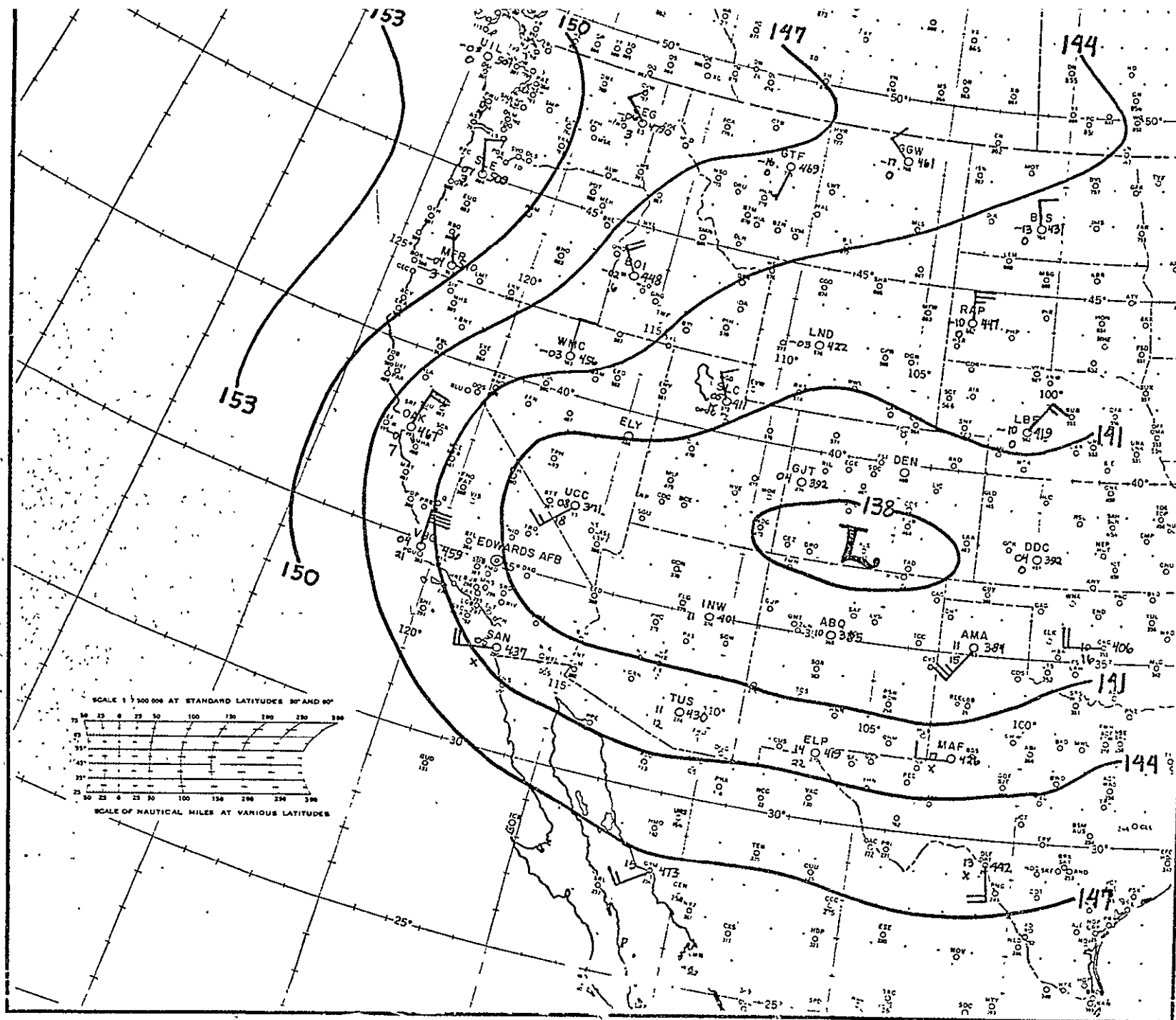


Figure C-37. - 850 mb Analysis, 0000GMT, February 15, 1975. Heights in gpdam.

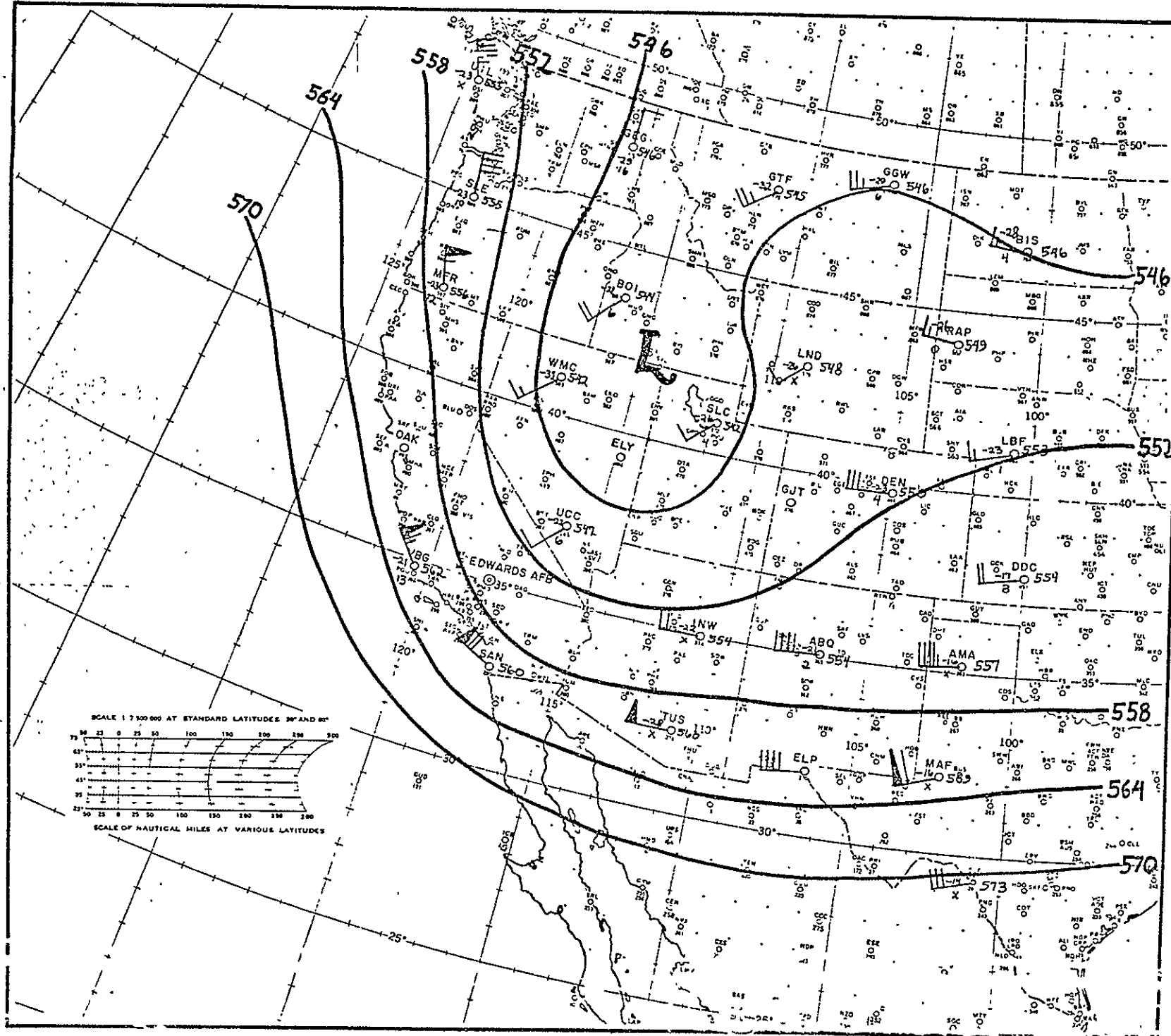


Figure C-38 500 mb Analysis

was accompanied by a veering in wind direction (i.e. change in a clockwise sense) towards the north and 13 m sec^{-1} wind speed increases in southern California. Further aloft, winds at the jet stream level similarly changed to a more northerly direction by 0000 GMT and were nearly parallel to the Sierra ridge line, with slightly higher speeds than at 1200 GMT.

(b) Rawinsonde and Aircraft Data.- The 1200 GMT rawinsonde at Oakland, CA, taken upwind and 9-1/2 hours before the B-57B flight, was the sounding most representative of meteorological conditions over and east of the Sierra at flight-time. Vertical wind shears at Oakland were generally small except in the layer from 10.8 to 11.7 km where the maximum shears were $16.9 \text{ m sec}^{-1}/\text{km}$ ($.017 \text{ sec}^{-1}$) and higher. A shear of $.046 \text{ sec}^{-1}$ and an Ri of 0.24 were calculated for the layer between 9.5 and 9.8 km from B-57B sounding data taken over the southern Sierra Nevada mountains.

Wind speeds in the lowest 2.5 km varied from 13 to 20 m sec^{-1} in the flight area. Wind speed changes in the lowest km were not especially large at any rawinsonde station near the flight area, or on the B57B climbout and descent soundings. The only significant wind direction change noted near the surface was observed on the Edwards AFB 2000 GMT (1200 PST) sounding where the wind veered from 270° at the surface to 307° at 3.0 km altitude. Winds measured in flight showed a 15 m sec^{-1} speed decrease along the flight path just prior to and in the early stages of the severe turbulence. This decrease was probably related to the terrain effects as well as to the turbulence itself, which tends to transfer momentum from the main flow to smaller scale eddies. Temperature changes during the runs were not especially pronounced except on run 7 (2.5 km altitude) where 6°C to 8°C wave-like changes took place over distances (wavelengths) of 14 to 28 km. The run was at an angle of

approximately 25 degrees to the main ridge line of the Tehachapi mountains and from 40 to 70 km from the ridge. Aircraft altitude variations were in phase with the temperature changes. The only significant inversion noted on any of the three B-57B soundings taken in the area was a change of 4°C in 50 m at 2.0 km. If it were assumed that a similar inversion existed on run 7, the temperature changes on this run might largely be attributed to altitude excursions. Had there been no inversion, or perhaps at best only a weak one, the temperature changes would probably have been due to wave motions in the atmosphere which in turn affected the altitude of the aircraft.

Observations in flight showed mostly cloudy conditions over the mountains with buildups to 8.5 km above the Inyo mountains. Deserts and valleys had only scattered cumulus with bases around 2.1 km. Some wave clouds were noted at flight level (2.6 km) during run 8. Figure C-39 shows a rotor cloud observed on this run.

Discussion

The absence of significant high altitude turbulence east of the Sierra was not surprising due to the large deviation of the wind direction from orthogonality to the ridgeline. The low level turbulence was primarily mechanical, resulting from high surface wind speeds in an area with irregular terrain features. Wind direction and speed changes were for the most part not a significant feature in the formation or the continuance of the turbulence. However, some areas of severe turbulence appear to have been directly related to terrain features and had a close association with horizontal wind speed shears as measured from aircraft data.



Figure C-39.- Rotor Cloud Observed on Flight 28.

Flight 29, February 20, 1975, 1107-1338 PST (1907-2138 GMT)

Flight Summary

The flight was scheduled to search for high altitude mountain wave turbulence east of the Sierra and low altitude orographic turbulence in the vicinity of Edwards AFB. Two runs (6 and 7) were made on the lee of the Sierra north and east of Lone Pine, CA. Run 6 was at 10.7 km in very light and occasionally light turbulence and run 7 at 7.3 km in patchy very light turbulence (fig. C-40). Both runs had some periods of a few seconds to two minutes in nearly smooth air. When the aircraft returned to the Edwards AFB area, a run (No. 8) was made at 1.2 km altitude on the lee side of the Tehachapis, roughly parallel to the main ridge line (fig. C-41). Turbulence was steady, but highly variable in intensity. The first half of the run had patches of severe turbulence of up to one minute in length. Turbulence intensity decreased significantly during the latter half of the run, where the distance between the aircraft and mountains was greater.

Meteorological Conditions

A slow moving weak cold front extended from southwestern Utah into southern California at 1200 GMT. At flight-time the front was located approximately over Edwards AFB. A deepening of the trough along the frontal zone resulted in an increased north-south pressure gradient, resulting in 10 to 13 m sec^{-1} northwesterly winds at the surface. The pressure drop was nearly 10 mb across the Sierra at flight-time. The gradient was expected to weaken, however, as ridging extended into the northwestern U.S. West-northwesterly winds were prevalent throughout California at upper levels where the flow was nearly zonal.

○ Bishop, CA



○ Beatty, NV
VORTAC

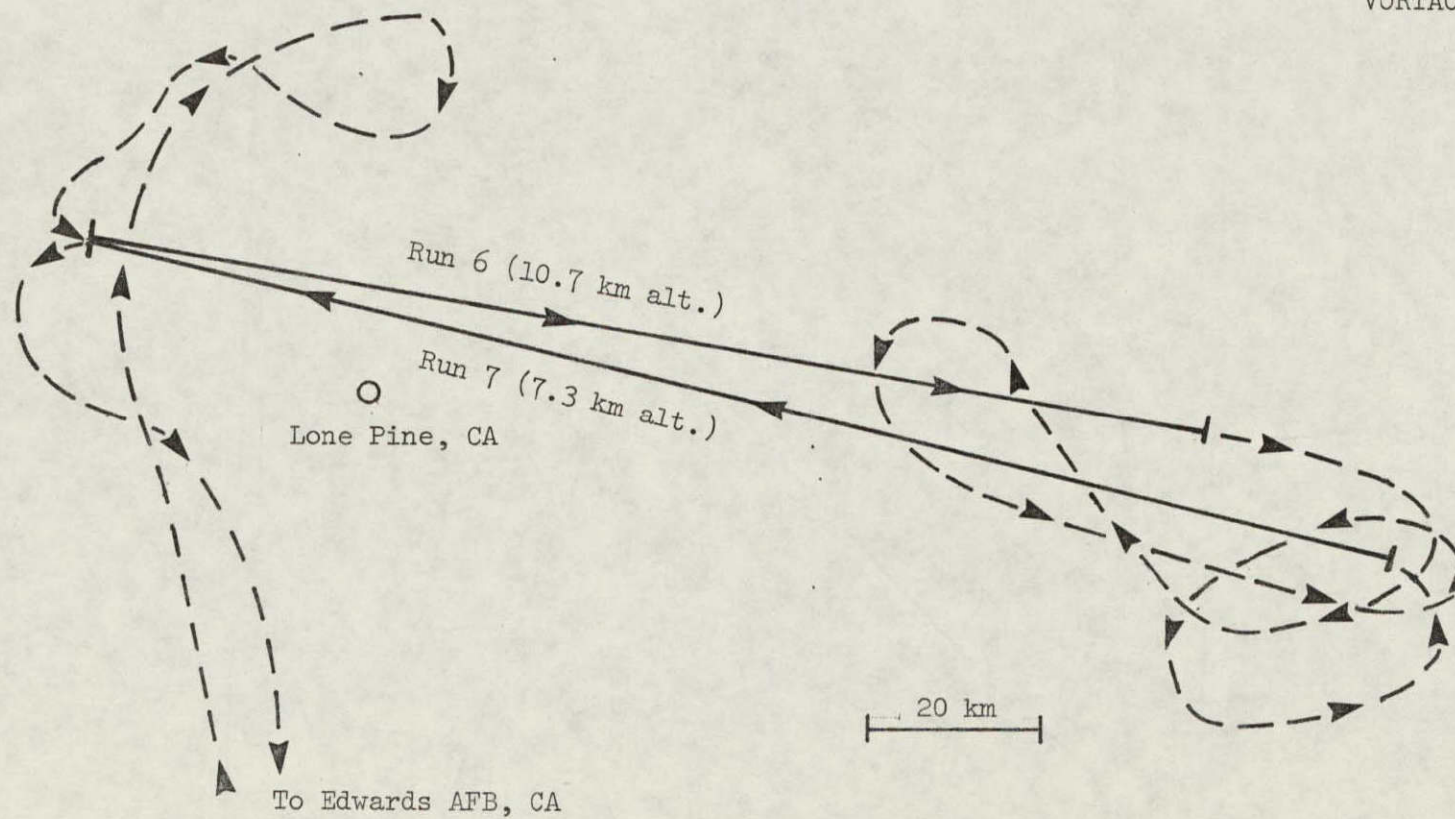


Figure C-40.- High Altitude track for Flight 29, 1907-2138 GMT, February 20, 1975.

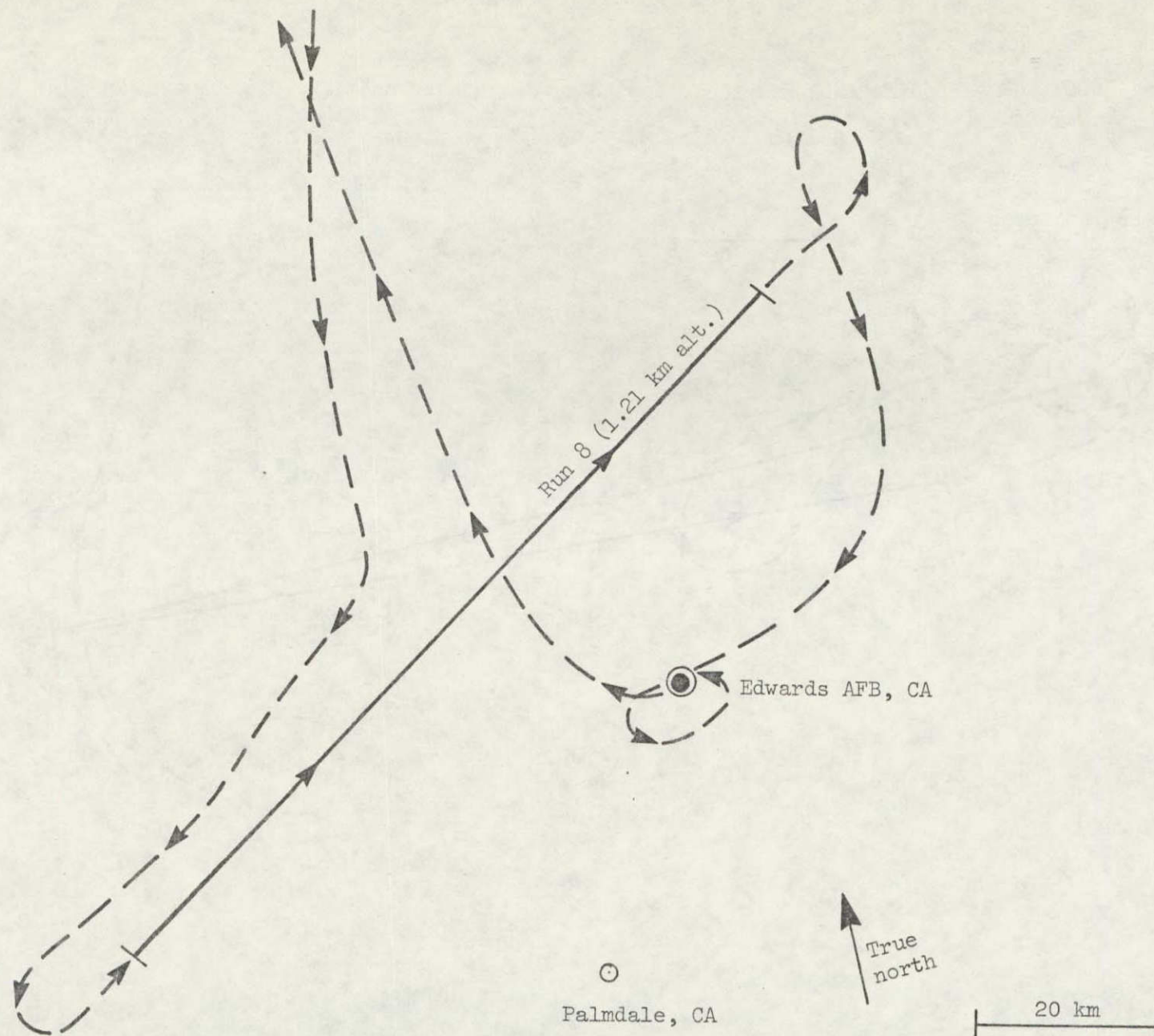


Figure C-41.- Low altitude track for Flight 29, 1907-2138 GMT, February 20, 1975.

Because of warm air advection in the Gulf of Alaska, upper level ridging that resulted was accompanied by a deepening of the trough to the southeast during the day, and a change in the flow over California to more northerly.

Vertical wind shears were less than $.010 \text{ sec}^{-1}$ at Oakland, Vandenberg AFB, and Edwards AFB, CA at all levels except above 12.2 km at Oakland. Shears of greater than $.034 \text{ sec}^{-1}$ existed near 10.4 km at Yucca Flats, NV. A moderately strong tropopause inversion was present at Oakland and Yucca Flats. There were no indications of an upper frontal zone associated with the surface troughing.

Inflight measurements showed a wind of $240^{\circ}/57 \text{ m sec}^{-1}$ on run 6 at 10.7 km, little changed from the 1200 GMT rawinsonde winds. A large wave-like temperature change occurred on the run (fig. C-42), centered just east of the crest of the Sierra. The temperature decreased 4.4°C and increased 4.8°C over a distance of 34 km. On run 7, no similar indications of wave activity were noted on the temperature time history. Several bands of lenticular wave clouds were observed east of the Sierra at an altitude of around 7.6 km. These are shown on fig. C-43. However, they dissipated during run 7 as the B-57B was attempting to fly towards them. Extensive cirrus cloudiness was noted, especially north of Lone Pine. The base altitude of the cirrus clouds increased from 7.3 km in this region to 9.1 km above the southern Sierra.

On the low altitude run 8, which was flown at an altitude below the crestline of the **Tehachapi mountains**, two significant warm zones were encountered where the temperature increased (followed by a comparable decrease) 13°C to 14°C (fig. C-44). The run was at a relatively small angle to the main ridgeline of the **Tehachapis**, which makes it unlikely that the warm zones (separated by 32 km) represented successive troughs in an

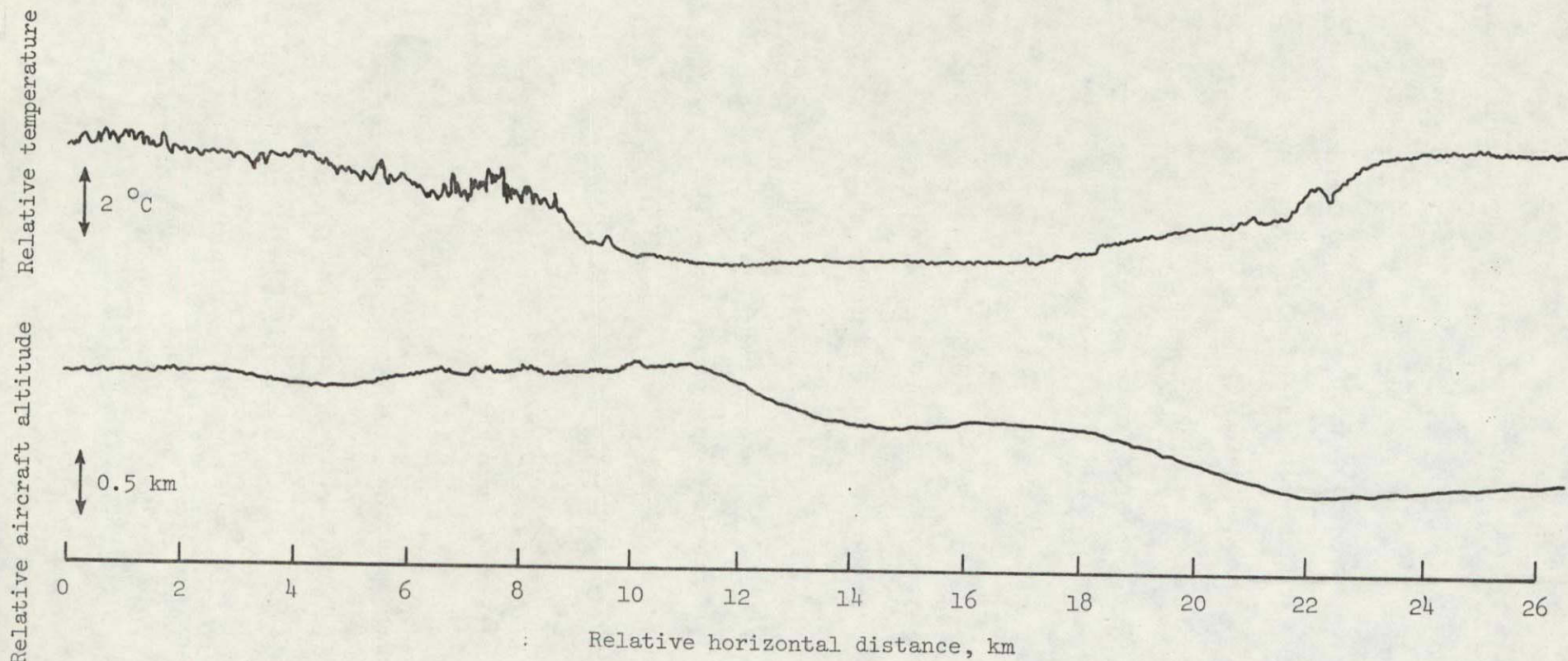


Figure C-42.- Wave structure in temperature pattern observed east of Sierra Nevada on run 6, Flight 29.



Figure C-43.- Lenticular Clouds Observed East of the Sierra Nevada on Flight 29.

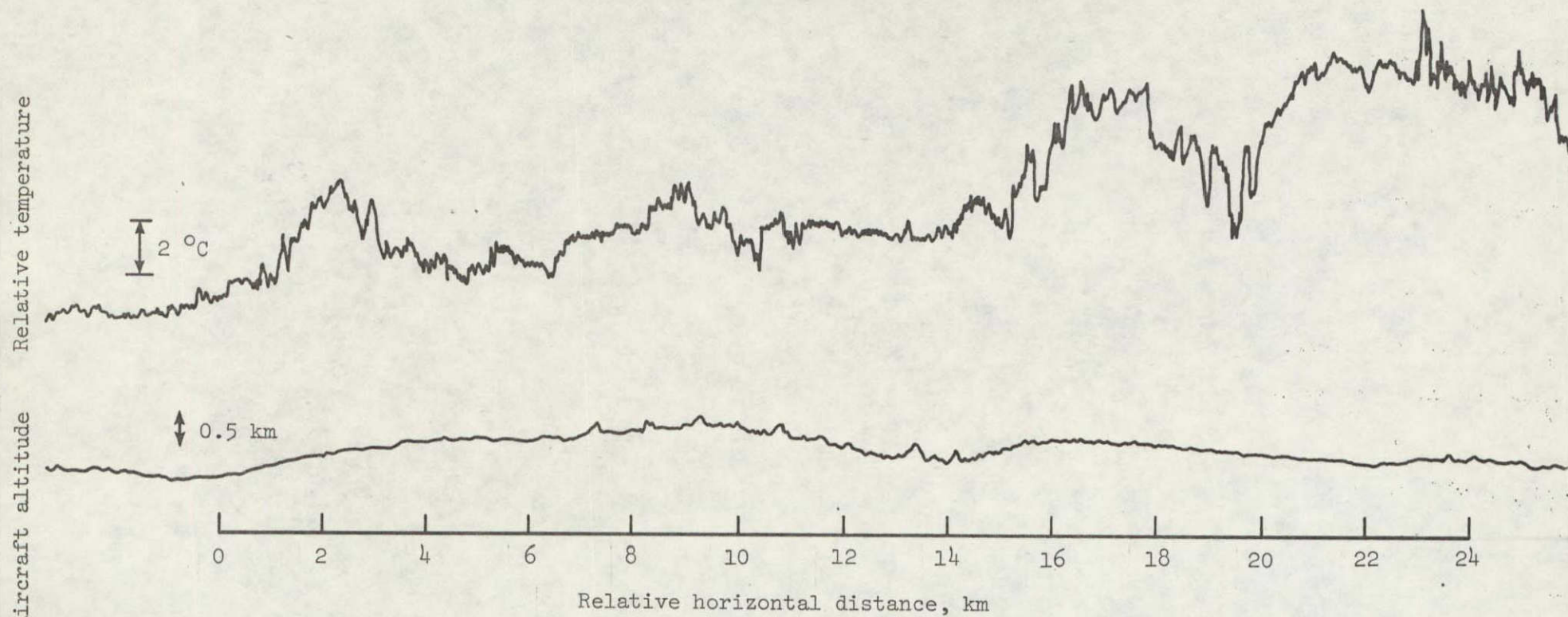


Figure C-44.- Wave structure in temperature pattern on run 8, Flight 29.

(a) First warm zone.

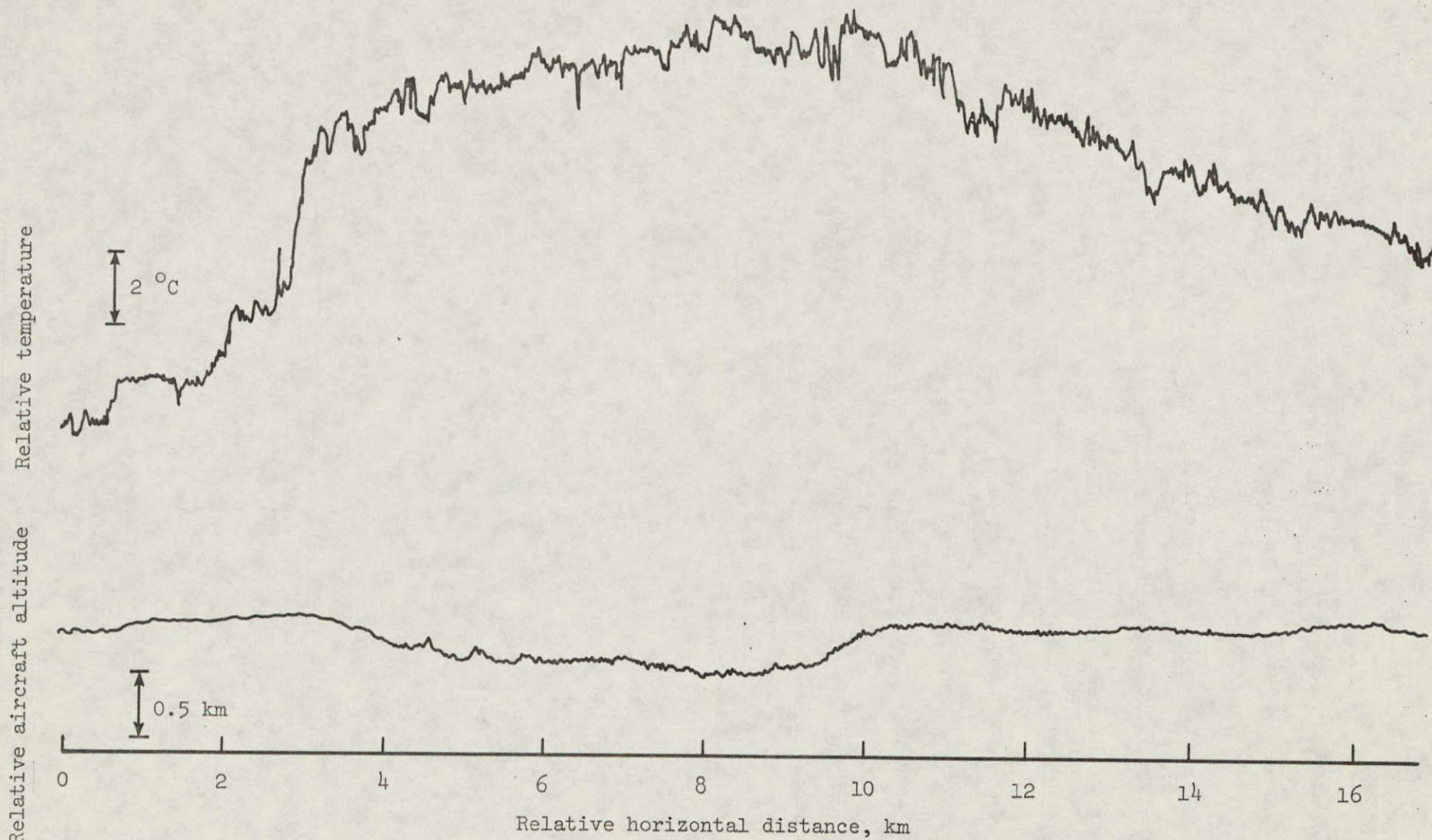


Figure C-44.- Concluded.

(b) Second warm zone.

orographically generated wavetrain. It is possible that the warm zones were related to descending air below two separate mountain passes.

Discussion

Lack of significant mountain wave turbulence east of the Sierra was related to the wind direction being non-orthogonal to the ridge line. During the flight, winds became more parallel to the ridge, the lenticular clouds dissipated, and turbulence decreased. The intense but highly variable low level orographic turbulence was typical of high wind conditions where the direction is roughly orthogonal to a non-uniform ridge. Significant change in average intensity of the turbulence from the first to the second half of a run was due mostly to the aircraft's departing from the rotor zone.

Flight 30, March 7, 1975, 1442-1747 PDT (2142-0047 GMT)

Flight Summary

Large negative wind shears above the jet stream and a report by a NASA F-104 of continuous light turbulence at 14.6 km above Edwards AFB prompted this mission. The B-57B climbed to 14.3 km in the vicinity of Edwards AFB where run 2 (fig. C-45) was taken in almost totally smooth air. A search was made at the same altitude east of the Sierra near Owens Lake but no turbulence was found. The aircraft returned to the Edwards AFB area, where six runs were made. Four of the runs were parallel to and above the upwind edge of a large standing lenticular shaped cloud (fig. C-46); the other two were orthogonal to the cloud edge. The runs were all within a 600 m altitude band centered at 14.5 km and were approximately 7 km above the top of the lenticular cloud. On runs 3 and 9, which were orthogonal to the cloud's edge, short patches of very light turbulence approximately 6 km long and some moderate wave action were encountered near the cloud's edge. Runs 4, 5 and 6, which were parallel to the cloud's edge, had a total of only 22 km of very light to light turbulence. The pilot had difficulty on these runs in keeping the aircraft parallel to the cloud's edge. Intermittent turbulence, lasting for 110 km, occurred on run 8 and ranged from very light to light-moderate short smooth patches. Brief encounters with very light turbulence were noted on the climbout at 5.9 km and on the descent at 11.9 km. Light to light-moderate turbulence occurred on the climb between 0.9 and 1.8 km and on descent between 3.0 and 2.7 km. The only pilot reports of turbulence in California other than from the NASA F-104 were either in clouds or below 4.6 km.

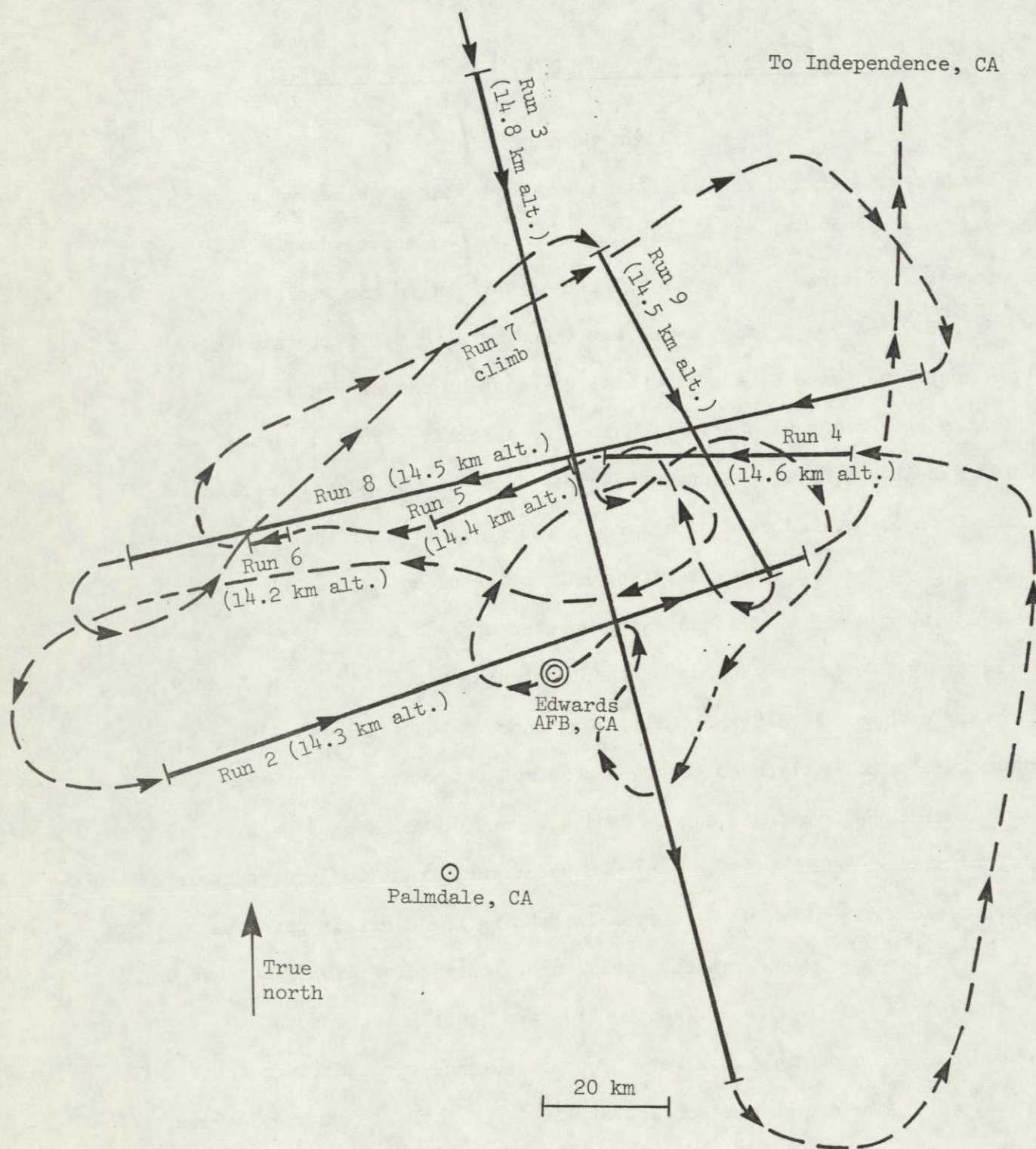


Figure C-45.- Track for Flight 30, 2142-0047 GMT, March 7, 1975.



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Figure C-46.- Lenticular Cloud Observed in Standing Wave East of the
Sierra Nevada on Flight 30.

Meteorological Conditions

Surface winds on March 7 at 1200 GMT in central and southern California were generally from the south or south-southeast at 5 to 10 m sec^{-1} along the Pacific coast and at 3 to 5 m sec^{-1} inland. Flow around a 990 mb low, located 370 km west-northwest of San Francisco was associated with extensive cloudiness and some precipitation in northern and central California. An occluded front extending from the low intersected the coast in the San Francisco Bay region. Southerly surface winds increased considerably as the day progressed, with many stations reporting gusts above 15 m sec^{-1} . Edwards AFB wind speeds remained fairly low, however, at least until the period of the B-57B takeoff. South to south-southwesterly winds at 850 mb , approximately the altitude equivalent of many of the coastal and transverse ridges in southern California, exceeded 26 m sec^{-1} at Oakland and Vandenberg AFB on the 1200 GMT RAOB but were only 5 m sec^{-1} at Edwards AFB. 700 mb winds at Edwards AFB were from $200^\circ/18 \text{ m sec}^{-1}$ at 1200 GMT and remained nearly the same until 1800 GMT when a special sounding was made. A moderate trough at 500 mb lay over the surface low in the Pacific at 1200 GMT. (fig. C-47). Lowest pressures were located 180 km west of the surface low. 500 mb winds at Edwards AFB were from the southwest and about 31 m sec^{-1} on both the 1200 GMT and 1800 GMT soundings, increasing with altitude to between 46 and 51 m sec^{-1} in the jet stream, which was located between 9.1 to 10.7 km . Winds were much stronger along the Pacific coast. The 150 mb chart, closest standard pressure level to the altitude of the data runs, showed winds of 41 to 46 m sec^{-1} from the southwest in Southern California. (Fig. C-48)

The flight was still in progress when the 0000 GMT (March 8) weather observations were made. The surface low located west of San Francisco

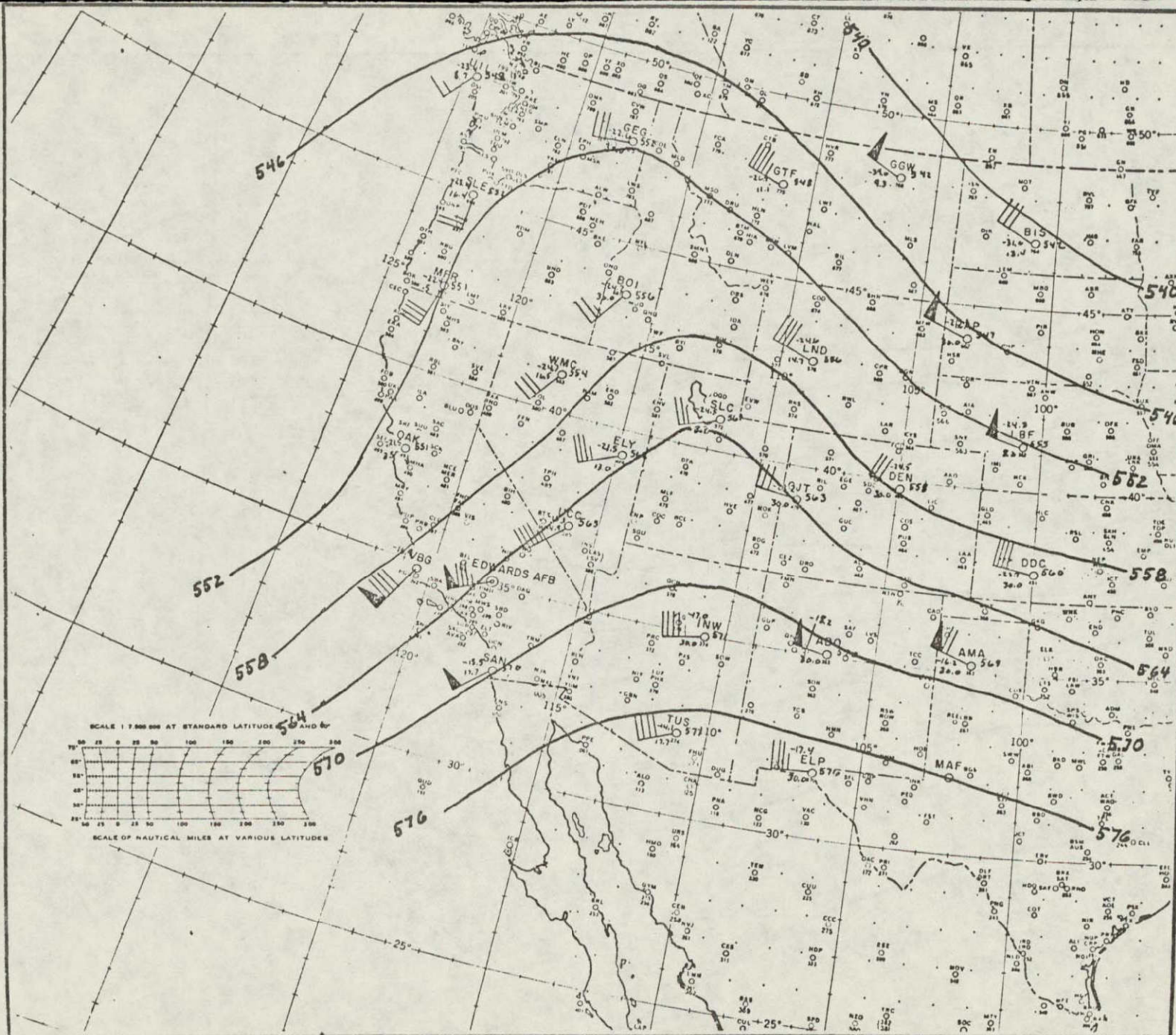
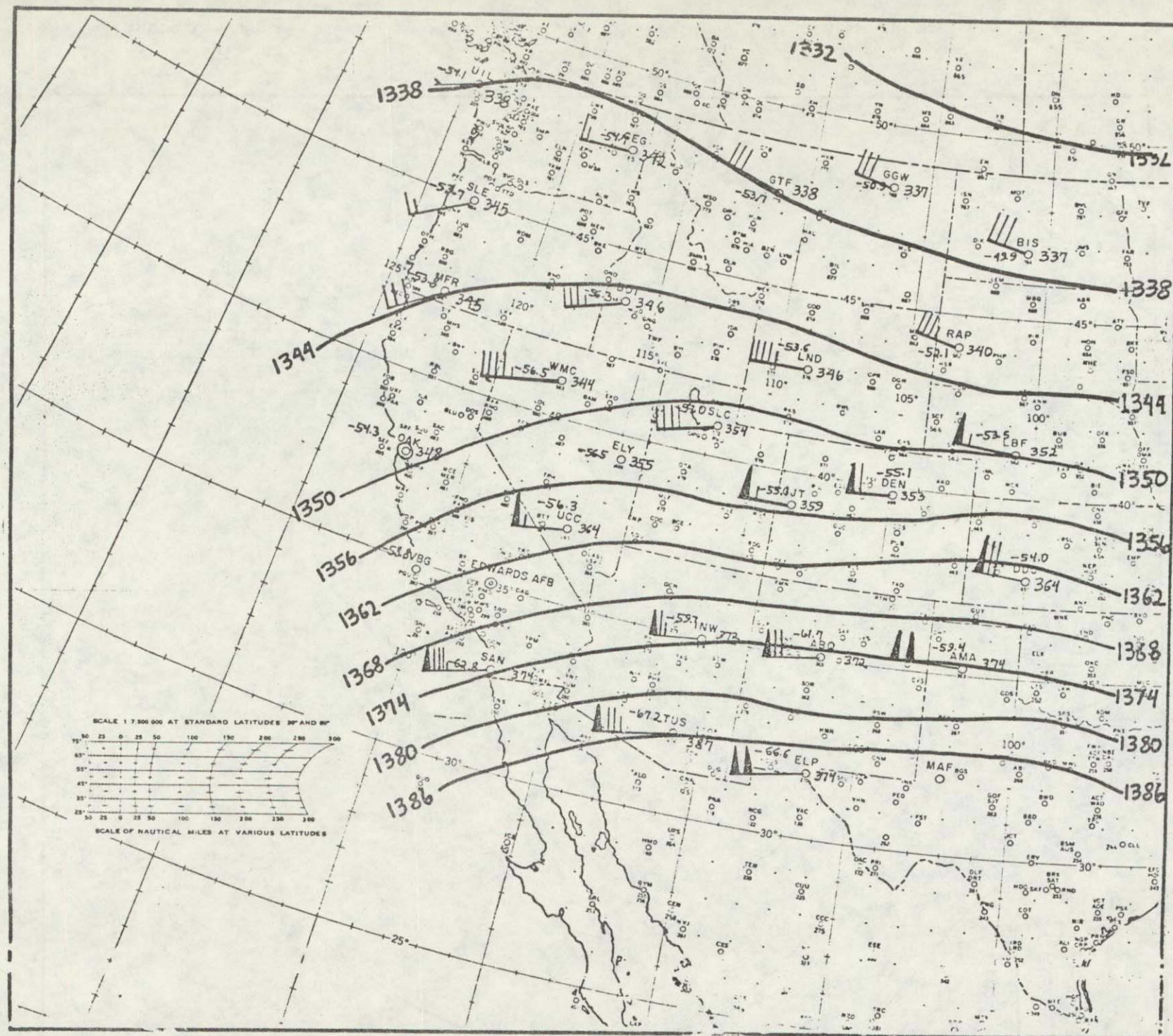


Figure C-47.- 500 mb Analysis, 1200 GMT, March 7, 1975. Heights in gpdam.



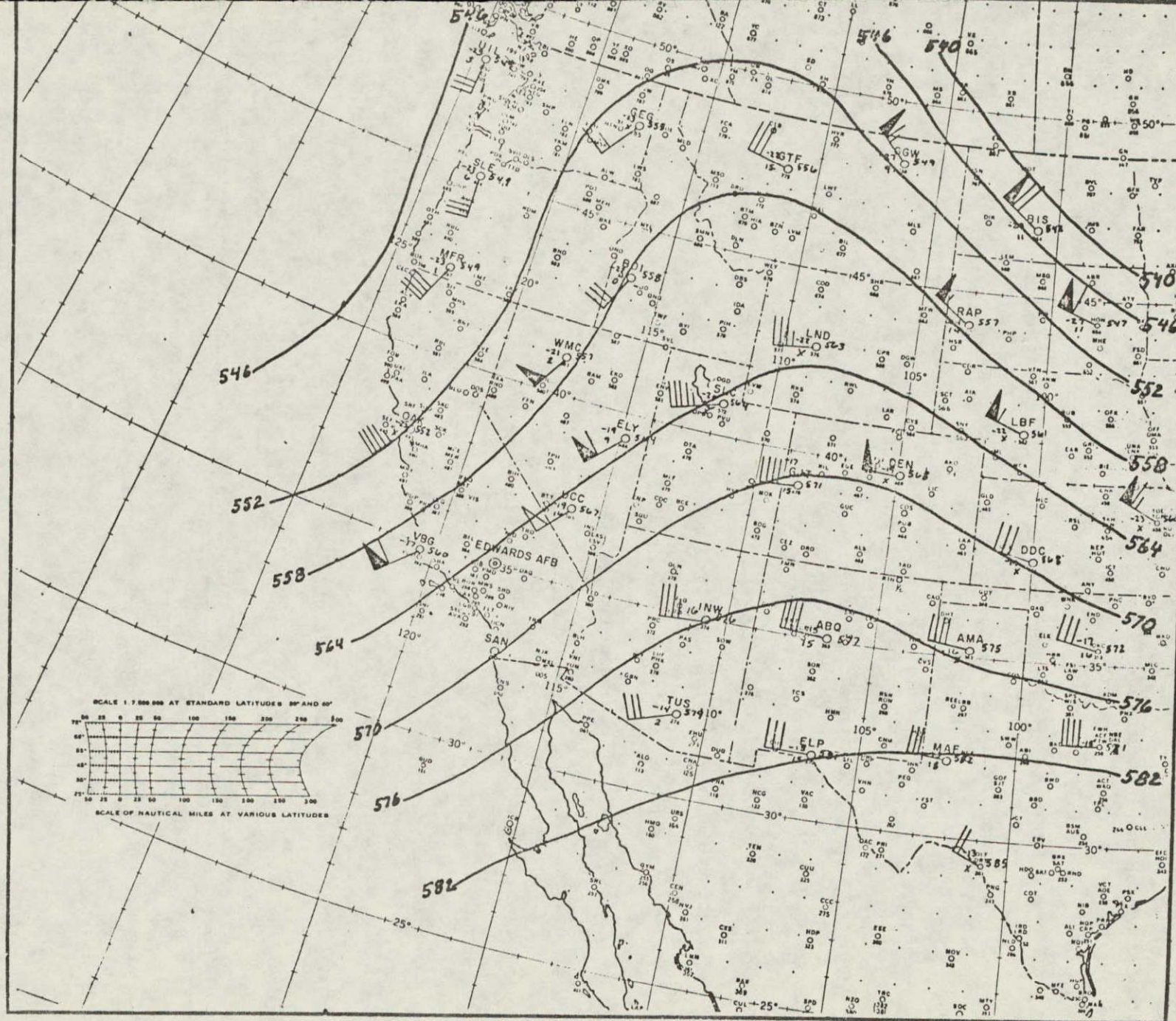


Figure C-49.- 500 mb Analysis, 0000 GMT, March 8, 1975. Heights in gpdam.

had moved north-northeastward and weakened, but winds remained moderately strong from the south. Ridge level winds to the south of Edwards AFB continued from around 205° but were somewhat weaker than at 1200 GMT. The 500 mb trough remained nearly stationary and winds were relatively unchanged from the previous 12 hours at most levels above 700 mb (fig. C-49).

Negative vertical wind shears of $.022 \text{ sec}^{-1}$ and greater, centered between 14.0 and 14.3 km, were observed above the jet stream on the 1000, 1800, and 0000 GMT soundings on March 7-8 at Edwards AFB. In addition, Oakland 1200 GMT and Yucca Flats 1200 and 0000 GMT observations had shears of like magnitude above the jet. The wind shears in the Edwards AFB area were located in either an isothermal or unstable layer above the tropopause inversion (fig. C-50). Richardson numbers computed for the 1800 GMT and 0000 GMT Edwards AFB shear layers were 0.22 and 0.42, respectively.

Several small and a few very large standing wave clouds were observed on March 7 to the lee (north) of the San Gabriel mountains. The largest one, a massive cirrostratus cloud, about 600 m thick and at least 90 km in length, was located 7.0 km to the north of Edwards AFB. Its upwind edge was oriented in line with run 8 (fig. C-45) or approximately along a line $075^{\circ} - 255^{\circ}$. The area to the north was generally overcast and scattered cumulus existed to the south. A wave-like perturbation in the top of the large lenticular cloud was observed approximately 18 km north of the cloud's leading edge. This cloud is shown on fig. C-51, a photograph taken from the surface at Edwards AFB. The edge of the cloud was observed to remain stationary for the entire day.

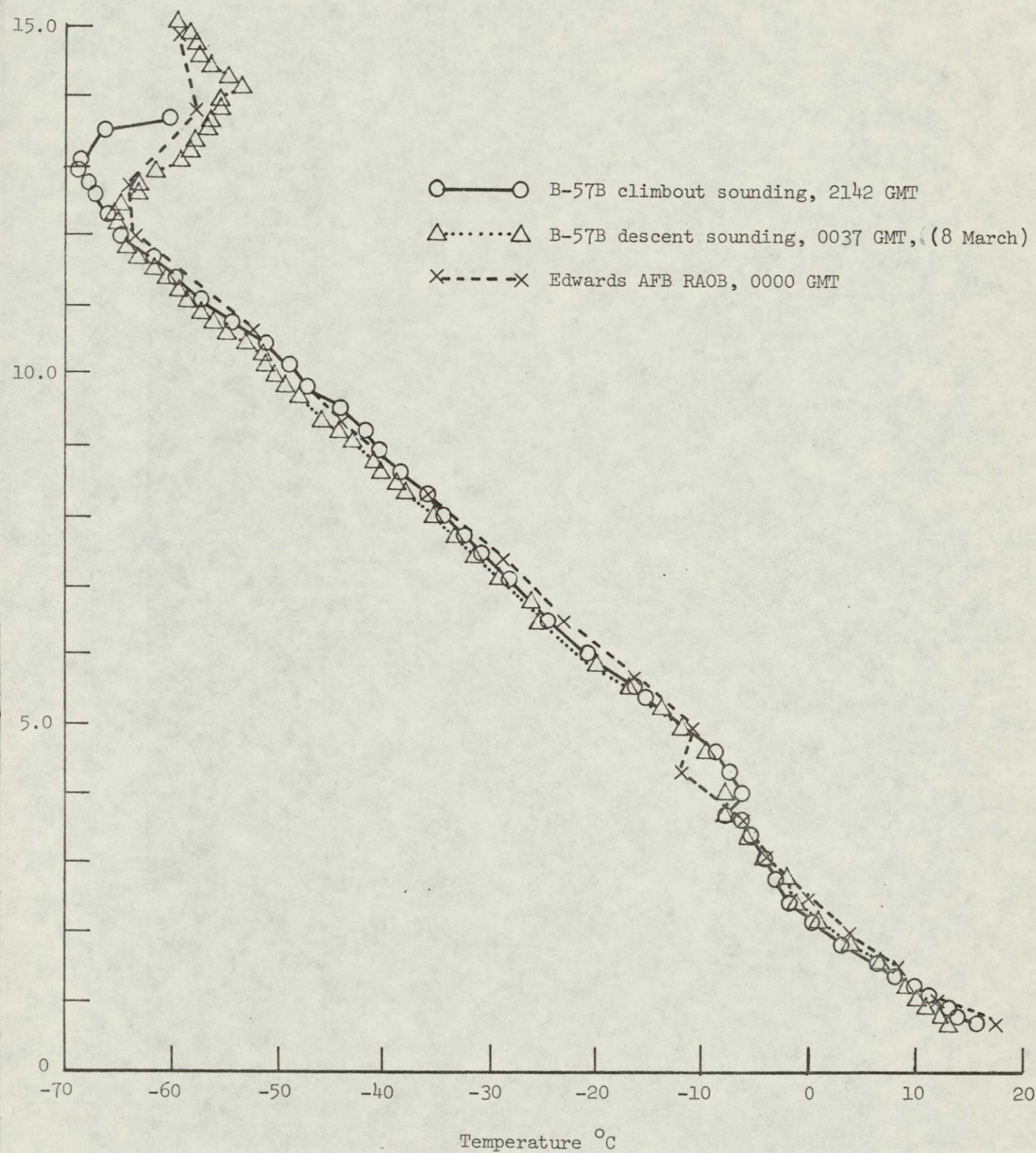


Figure C-50. - MAT B-57B and Edwards AFB, CA temperature soundings for Flight 30, March 7, 1975.

C-2



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Figure C-51.- Lenticular Cloud of Figure C-46, Viewed from Surface at Edwards AFB.

The two important runs for meteorological purposes were run 3 which was orthogonal to the southern edge of the massive standing wave cloud and run 8, flown above and parallel to the edge of the cloud. On run 3 wind speed variations of 5 to 13 m sec⁻¹ were noted, the highest speed (40 m sec⁻¹) coinciding with the peak altitude of the aircraft. In-flight temperature measurements showed a warm zone centered near the cloud's edge and another warming of 6° to 7°C near the end of the run. It appears from the average vertical velocity time history that the latter warming resulted from down-flow of air to the lee of the San Gabriel mountains. The mountain ridge is oriented 295° - 115° and the mean flow (as derived from B-57B data) was from around 250° or about 45° to the ridge line. The surface wind direction, estimated from surrounding weather station data, was nearly orthogonal to the ridge line (190° to 210°), however. It appears from the temperature and mean vertical velocity data that the wave motion generated from flow over the San Gabriel crest gradually diminished until the location of the large lenticular cloud where further amplification took place within a stable layer above the tropopause. Sounding data from the B-57B aircraft, obtained after run 8 showed a 100 m layer centered at 13.7 km where the temperature increased 3.3°C and the wind speed decreased 6 m sec⁻¹, resulting in a Richardson number of 0.47.

During run 8 temperature oscillations of 1°C to 3°C over 5 to 15 km wavelengths occurred but were not in any organized pattern as on run 3 (fig. C-52). Wind speed variations were not pronounced on the run. However, the direction shifted from SW to SSW towards the south in the middle of the run and then back to WSW by the end.

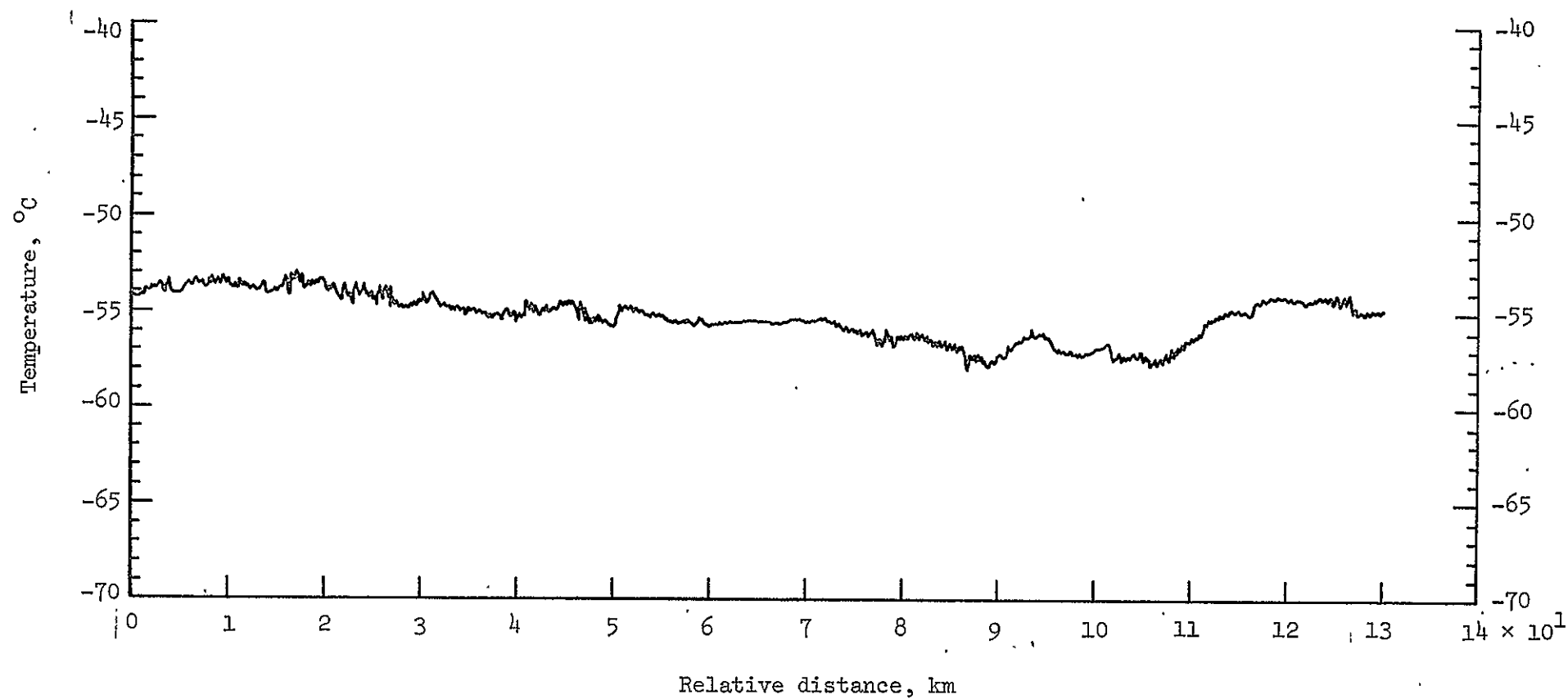


Figure C-52.- Temperature fluctuations observed on run 8, Flight 30 (altitude approximately 14.5 km)

Discussion

The only significant high level turbulence on the flight appeared to have had a direct association with the large standing wave cloud located 6-7 km below. The turbulence occurred in a narrow strip no more than 6 km wide and at least 90 km long and appeared to be confined to an altitude band of approximately 300 m. The layer containing the turbulence had large negative vertical wind shears and low Richardson numbers. Ridge-top winds were from the south-southwest at cloud height and turbulence level winds were at angle of 25° to the west. The long dimension of the cloud was oriented at 25° to the windflow at the cloud level (fig. C-53). Pilot observations on the B-57B flight and gust velocity data derived from the measurements showed that moderate wave activity existed to the lee of the San Gabriel mountains and extended well downwind. Gradual sloping terrain to the leeward side of the ridge may have produced a tilt in the wave train and, combined with increased moisture to the north, caused the formation of the standing wave clouds well downwind of the primary wave.

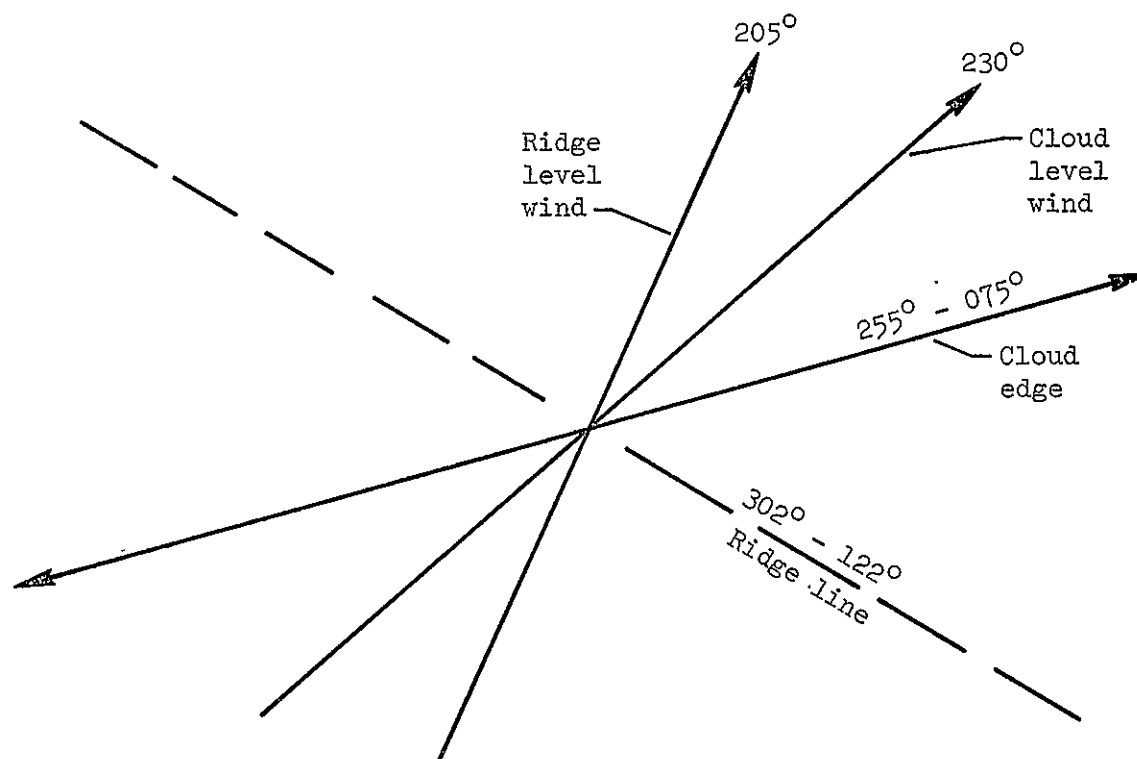


Figure C-53.- Orientations of cloud edge, ridge line and winds at ridge level (approx. 1.5 km alt.) and cloud level (approx. 7 km alt.) on Flight 30.

Flight 31, March 25, 1975, 1136-1418 PDT (1836-2118 GMT)

Flight Summary

Although there were indications that a Sierra wave was a possibility, the rapidly changing meteorological situation plus pilot reports of turbulence led to a planned flight over central Nevada in order to search for mountain wave turbulence. After a climbout east of the southern Sierra to 9.8 km the B-57B headed for Boulder City, NV where commercial pilot reports of moderate turbulence were received within the previous hour at 10.1 and 10.9 km. However, only patchy light turbulence was found at 10.9 and 12.5 km. The aircraft then continued to central Nevada and west to the Sierra where isolated patches of light turbulence were encountered near 9 km, to the lee of the ridges northeast of Coaldale, NV, and near Bishop, CA. Patchy, very light turbulence was noted throughout the flight between 8.5 and 13.1 km. No records were taken because the turbulence ceased almost immediately after each encounter. The pilot occasionally observed light wave action and noted one strong wave occurrence west of Boulder City. Lenticular clouds were profuse to the lee of most ridges at estimated altitudes ranging from 3 to 6 km.

Meteorological Conditions

The 1200 GMT surface map showed an extensive low pressure system centered in northern Nevada with a rapidly advancing cold front extending southwest from the low center through central California. West-southwest winds of around 8 m sec^{-1} in the central Sierra and 13 to 18 m sec^{-1} in Nevada existed at the levels of most ridges. Stronger surface winds from the northwest, evident along the coast at 1200 GMT, were expected to migrate

eastward during the day as ridging continued in British Columbia and the low pressure system moved eastward. Sea level pressure drop across the Sierra was only a moderate 8 mb. A shallow trough in the upper levels, moving into California at the time of the 1200 GMT observations was forecasted to deepen and slow considerably in the next 12 hours. Strongest winds aloft, exceeding 50 m sec^{-1} from the northwest at jet stream levels, were on the trailing edge of the trough. In Nevada, jet stream winds were generally southwesterly and at only 30 to 35 m sec^{-1} . Vertical wind shears of $.029 \text{ sec}^{-1}$ and greater were observed at selected levels on the Oakland, CA sounding between 11.0 and 12.5 km. Yucca Flats, NV and Edwards AFB had moderate shears greater than $.017 \text{ sec}^{-1}$ between 6.1 and 9.2 km. **Central and northern** Nevada RAOBS showed only weak shears. A significant decrease in wind speed above the jet stream north of Edwards AFB, as noted on the B-57B sounding, resulted in a wind shear of $.047 \text{ sec}^{-1}$ between 10.3 and 10.6 km. The layer was highly stable, however, with a R_i of 0.64. The strong inversion, noted in figure 3, above the tropopause is not seen on the Edwards AFB sounding where the balloon was released 14 minutes prior to the B-57B's takeoff. In addition to pilot reports mentioned near Boulder City, a report was received from a B-52 of moderate turbulence over Coaldale at 8.8 km five hours before the B-57B takeoff. A general cloud deck, with buildups to 6 km existed over the Sierra and ridges to the east. There was extensive cirrus cloud cover near 8.8 km over California and central Nevada.

Discussion

The patchy nature of the turbulence and the absence of strong wave activity may have been related to one or more of the following meteorological situations:

- (1) Extensive cloudiness reduced the chances of an inversion near the ridge levels.
- (2) The upper level trough was rapidly decelerating.
- (3) Vertical wind shears were not especially large in central and northern Nevada.
- (4) Winds at ridge levels across the central Sierra were of only moderate strength and were also shifting to a more northerly direction during the flight.

FLIGHT 32, March 26, 1975, 1246-1519 PDT (1946-2219 GMT)

As of this writing, flight 32 has been analyzed in greater detail than any other MAT mission; an analysis of the interesting meteorological situation therein is reported in reference 10. Therefore, the discussion of flight 32 in this report will be more comprehensive than the narratives for the other flights.

FLIGHT SUMMARY

This mission was planned to investigate an area east of the Sierra Nevada suspected to contain wind shear turbulence due to the large negative wind shears existing above a jet stream. About 4 hours prior to the B-57B takeoff, a Navy Sabreliner jet had reported an encounter with severe CAT just west of the Beatty, NV VORTAC at 12.2 km altitude. A NASA F-104 penetrated this area and verified the report about 3 hours before the B-57B takeoff. The F-104 reported the turbulence intensity to be moderate and centered near 13 km, extending well eastward of the Owens Valley. A second NASA F-104 searched the area only 30 minutes before the scheduled B-57B departure and confirmed the earlier NASA aircraft's findings.

After takeoff, the B-57B research flight proceeded north to Lone Pine, CA, just east of the Sierra Nevada. Locations of the six data runs, together with the associated geographical features, are shown in figure C-54. Aircraft-measured winds at the 13.0 km level are also indicated. The six data runs were in predominately easterly or westerly directions within an area roughly 80 km wide by 210 km long, lying between Lone Pine, CA, and Las Vegas, NV.

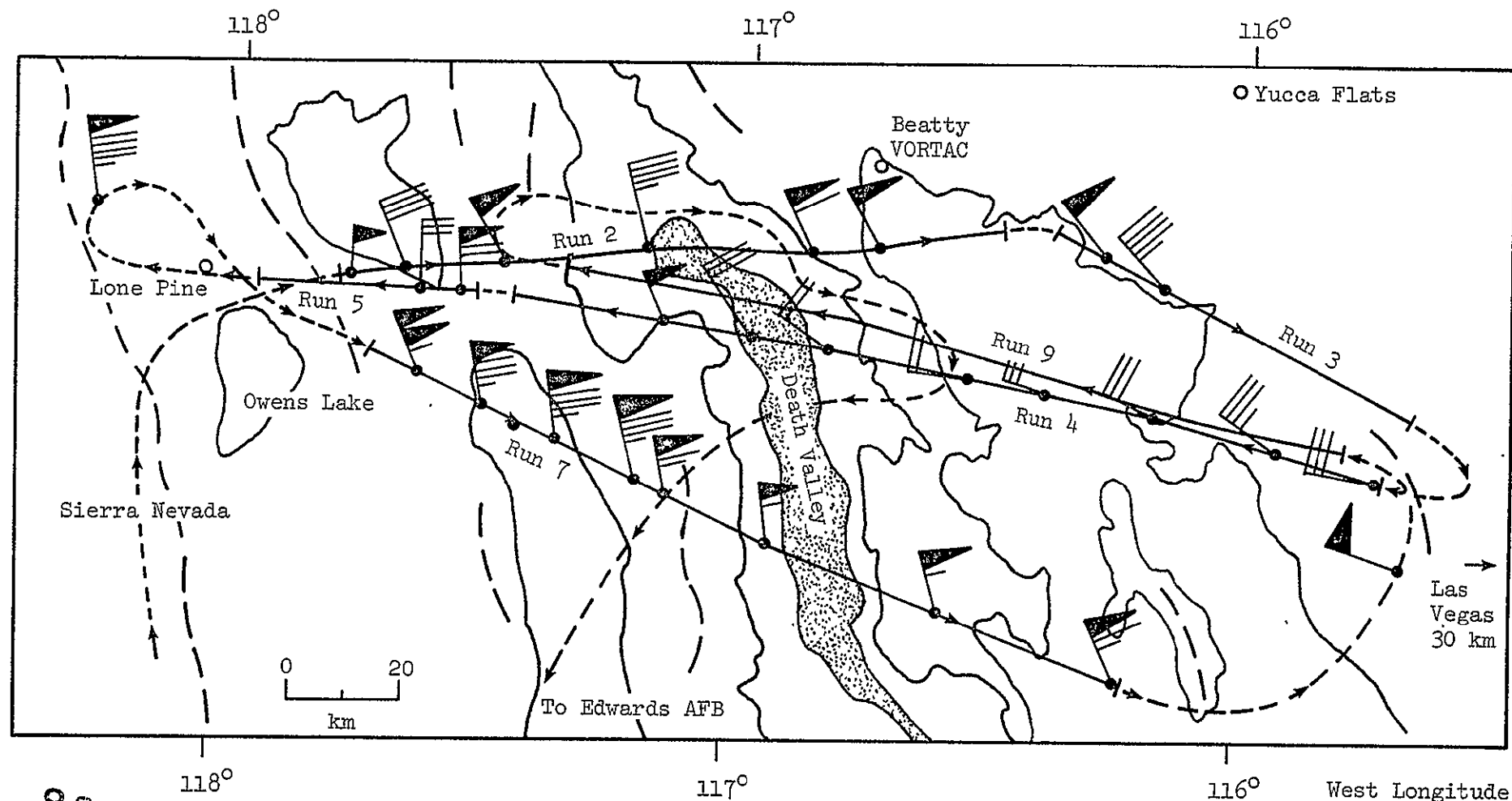


Figure C-54.- Flight track for 26 March 1975, including aircraft-measured winds at 13.0 km altitude. Major geographical features are indicated: area of Death Valley below sea level, 1 km elevation contours (—), and mountain ridges above 2 km (---).

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The terrain features consisted of a primarily mountainous area, including several mountain ridges, with the deep ground trough of Death Valley in the middle of the flight area and the shallower Panamint Valley immediately to the west. Only scattered clouds were observed during the flight, but considerable blowing dust was noted in the valleys, indicating strong surface winds.

The general features of the six data runs for this mission are listed in table C-2. The table includes duration and length, average speeds, and the standard deviations of the gust velocity components. All runs had an average altitude of about 13 km. In addition to the six data runs, four wind and temperature sounding runs (runs 6, 8, 10, and 11), where the aircraft changed altitude at least 1 km, were made to the west and east of as well as within the turbulence area.

Two of the six data runs (4 and 9) made by the B-57B were in fairly steady turbulence for at least 120 km. The turbulence appeared to extend in some areas at least 50 km in a north-south direction, but diminished considerably on the western, eastern, and southeastern sections of the search area. On four runs (2, 4, 7, and 9) a relatively short burst (5 to 13 km duration) of moderate to moderate-severe turbulence occurred. Mesoscale wind and temperature variations of pronounced magnitude occurred within the turbulent zone and are discussed in detail in reference 10.

METEOROLOGICAL CONDITIONS

On the morning of March 26, 1975, synoptic conditions did not appear favorable for mountain waves east of the Sierra Nevada because the general flow was directed nearly parallel to the main ridges. There was evidence, though, of large horizontal wind shears in this region which were associated with an upper level trough over Nevada.

TABLE C-2

FLIGHT INFORMATION FOR THE SIX DATA RUNS OF FLIGHT 32.

RUN	2	3	4	5	7	9
Start time (GMT)*	20:18:44	20:29:55	20:38:34	20:53:46	21:10:14	21:31:55
End time (GMT)*	20:29:18	20:36:03	20:53:16	20:57:27	21:21:53	21:44:56
Duration (min)	10.57	6.14	14.70	3.68	11.66	13.03
Length (km)	118.9	73.0	163.9	38.9	143.4	140.9
Avg. ground speed (m sec ⁻¹)	187	198	179	176	205	180
Avg. true airspeed (m sec ⁻¹)	183	177	188	185	187	189
Avg. flight direction (deg)	085	117	281	272	113	282
Standard deviation of U_g	3.33	3.18	4.36	4.35	5.70	3.22
turbulence velocity V_g	8.30	4.74	7.91	4.57	8.75	9.21
(m sec ⁻¹) W_g	2.22	2.04	2.34	1.20	1.52	2.15
Avg. altitude (km)	13.0	13.1	13.0	13.0	13.1	13.0

* Subtract 8 hours for local time (PST)

The surface map for 1200GMT on the 26th, approximately 8 hours prior to the B-57B's takeoff, showed a large low with a central pressure of 992 mb located in southwestern Colorado and northern New Mexico. A strong pressure gradient existed between the low and a high situated off the Oregon coast. Surface winds in California and western Nevada were generally from the northwest and averaged 10 to 15 m sec⁻¹. The axis of a rather narrow trough at 500 mb extended through Idaho and Nevada, with northerly winds exceeding 45 m sec⁻¹ on its western side throughout California. The winds decreased rapidly toward the axis of the trough in Nevada. Sharp curvature in the flow and pronounced horizontal wind shear were present over east-central California and southwestern Nevada. Above the jet stream, the trough appeared to be much broader. Temperature data from rawinsonde soundings taken at 1200GMT on the 26th and 0000GMT on the 27th are shown on figure C-55 for Oakland, CA, and Yucca Flats, NV, along with temperatures measured during the B-57B climb. The tropopause was 4 km lower at Yucca Flats than at Oakland on the 1200 GMT soundings, and near 12 km (193 mb) in the flight area. Cold air was being advected into southern Nevada below 7.5 km and into California at higher levels. (By 0000 GMT warming had occurred over Yucca Flats between 4 and 8 km, while Oakland experienced a slight cooling above 12 km.)

No wind data existed at Oakland or Vandenberg AFB, Calif., above the jet stream at 1200 GMT; consequently, vertical wind shears could not be computed for these altitudes west of the flight area before takeoff. However, the large horizontal temperature gradient along with significant speed and direction changes in the geostrophic wind indicated favorable conditions for wind shear turbulence east of the Sierra Nevada.

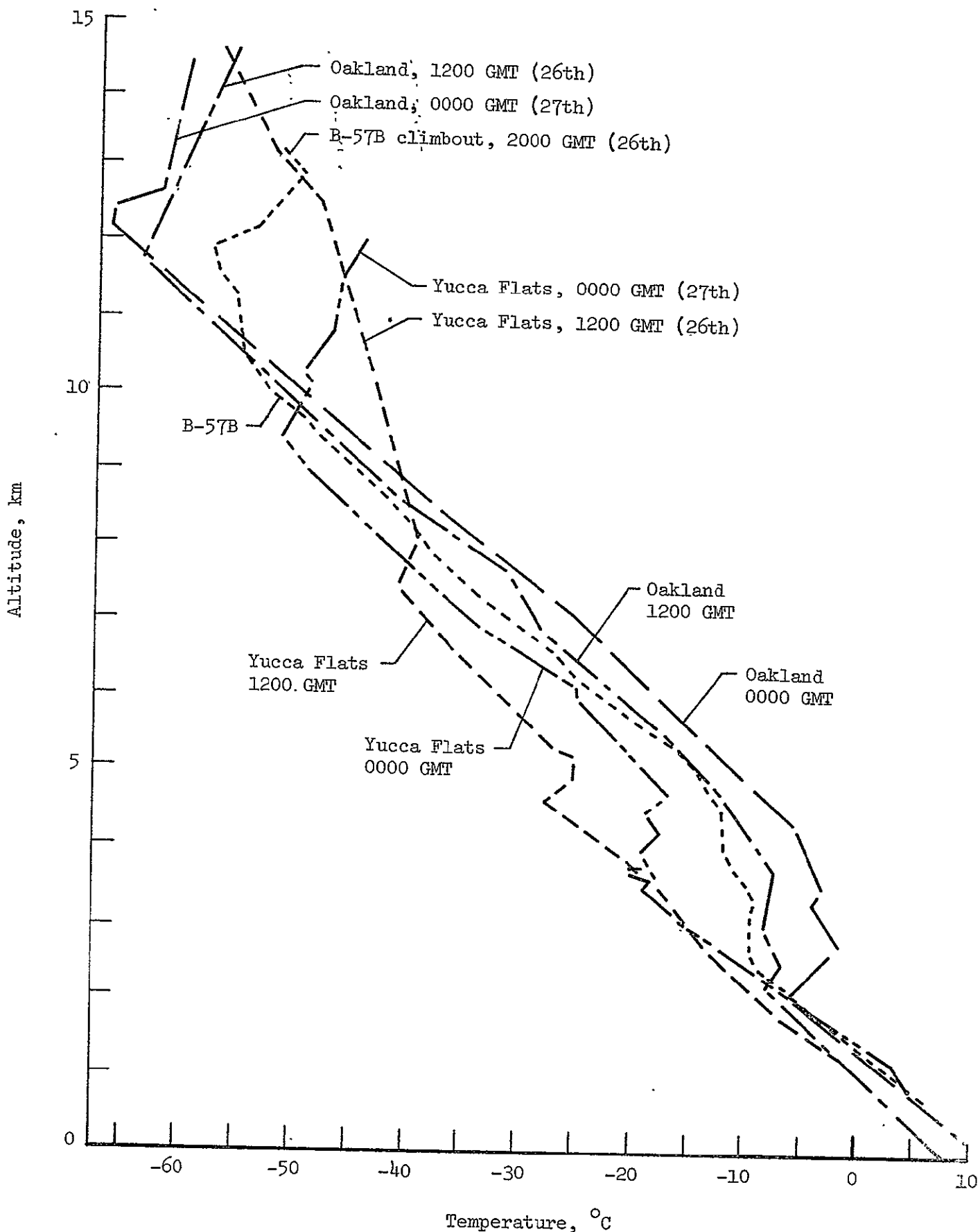


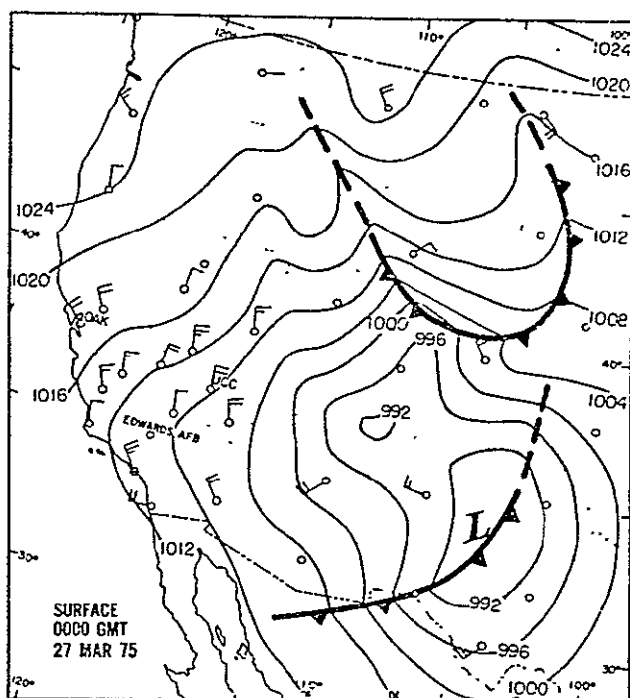
Figure C-55.- Oakland, CA, and Yucca Flats, NV, rawinsonde temperature soundings for 1200 GMT on 26 March, and 0000 GMT on 27 March 1975. B-57B climbout temperatures (2000 GMT on 26 March) are included.

At 0000 GMT on the 27th, about 2 hours after the B-57B had landed, the surface low had moved southeastward during the day and was accompanied by decreasing winds and a weakening pressure gradient to the west (fig. C-56a). Pressure ridging from Canada into Montana and Wyoming resulted in the surface winds shifting more towards northerly in the flight area. The 500 mb trough (fig. C-56b) remained quite narrow, but its southern portion was farther east than at 1200 GMT. The wind changed at Yucca Flats, from $210^{\circ}/7 \text{ m sec}^{-1}$ at 1200 GMT to $345^{\circ}/50 \text{ m sec}^{-1}$ at 0000 GMT. The jet core in California had shifted eastward during this period, and wind speeds increased by 15 m sec^{-1} in northern Nevada at 150 mb (13.6 km). The trough orientation at 150 mb was similar to that at 500 mb (fig. C-56C).

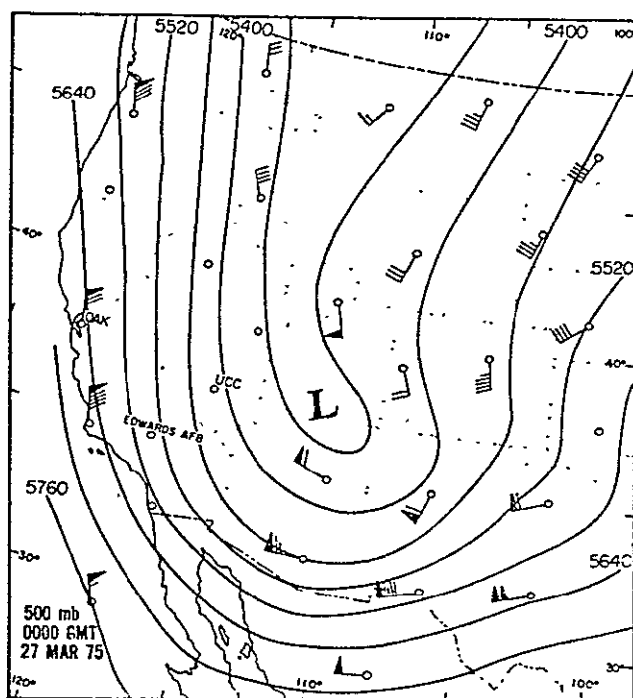
A temperature gradient of 22°C existed at 188 mb (12.2 km) between Oakland and Yucca Flats on the 0000 GMT sounding (fig. C-55). (See also temperature analysis at 200 mb in figure C-56d.)

The B-57B climbout sounding on figure C-55, which was representative of an area 220 km to the southwest of Yucca Flats, showed little change from the descent sounding (not shown). The tropopause remained at around 12 km in this region.

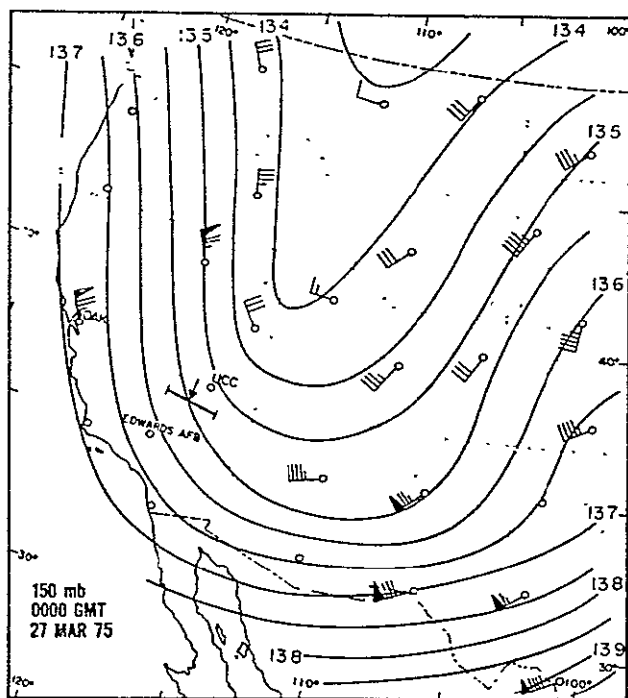
Vertical wind shears in the light wind region east of the jet maximum were small, as expected. Oakland had negative shears greater than -0.030 sec^{-1} at 0000 GMT near 11.9 and 13.4 km. A negative shear of 0.048 sec^{-1} was calculated from B-57B sounding data on run 10, taken just upwind of the turbulence area. However, part of the shear may have been horizontal rather than vertical. It appears from the sounding data in figure C-55 that the flight area, located west of Yucca Flats and north of the B-57B climbout, may have been in a region where the subtropical tropopause was overlapping the polar tropopause. The flight altitude was approximately 1 km above the higher tropopause.



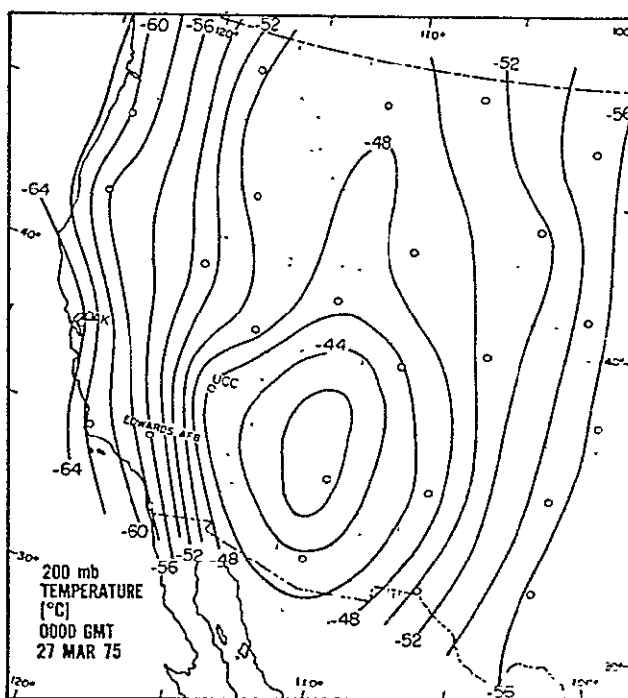
(a)



(b)



(c)



(d)

Figure C-56.-- Surface pressure (a), 500 mb (b) and 150 mb (c) contours, and 200 mb temperature chart (d) for 0000 GMT on March 27, 1975. The flight area is indicated by a solid line on the 150 mb chart.

DISCUSSION

Inspection of the time histories of turbulence and meteorological parameters derived from the aircraft measurements over Death Valley on this mission revealed several significant features. Especially noteworthy are the steep gradients, rapid fluctuations, and wave-like features of the wind and temperature in and around the turbulent area. Described in this section is the association of these phenomena with the intense turbulence patch that occurred over Death Valley and with the turbulence field in general.

In figure C-57 the vertical turbulence velocity for all six runs (summarized earlier in Table C-2) is plotted against ground distance in a basic west to east direction (the time histories of runs 4, 5, and 9 have been reversed in order to correspond to the other runs). The data runs are ordered (top to bottom) from north to south. The area of Death Valley below 1 km elevation is indicated. The vertical air motions show an area of light to moderate turbulence containing zones of more intense turbulence. One zone is centered just west of the 117° west meridian and coincides closely with the center and western fringe of the Death Valley depression. A second zone starts at the eastern edge of the depression, and gradually diminishes eastward. Both the relatively fixed location and the long duration of the zones are evidence of the relationship of the zones to terrain features.

The aircraft measurements revealed steep gradients, rapid fluctuations, and wave-like features in the wind and temperature fields, which were associated with the general turbulence field and with the more intense turbulence zones. As an example, time histories of the turbulence velocity and meteorological data for the combination of runs 4 and 5 are plotted in figure C-58 as functions of the ground distance. The running time averages listed in

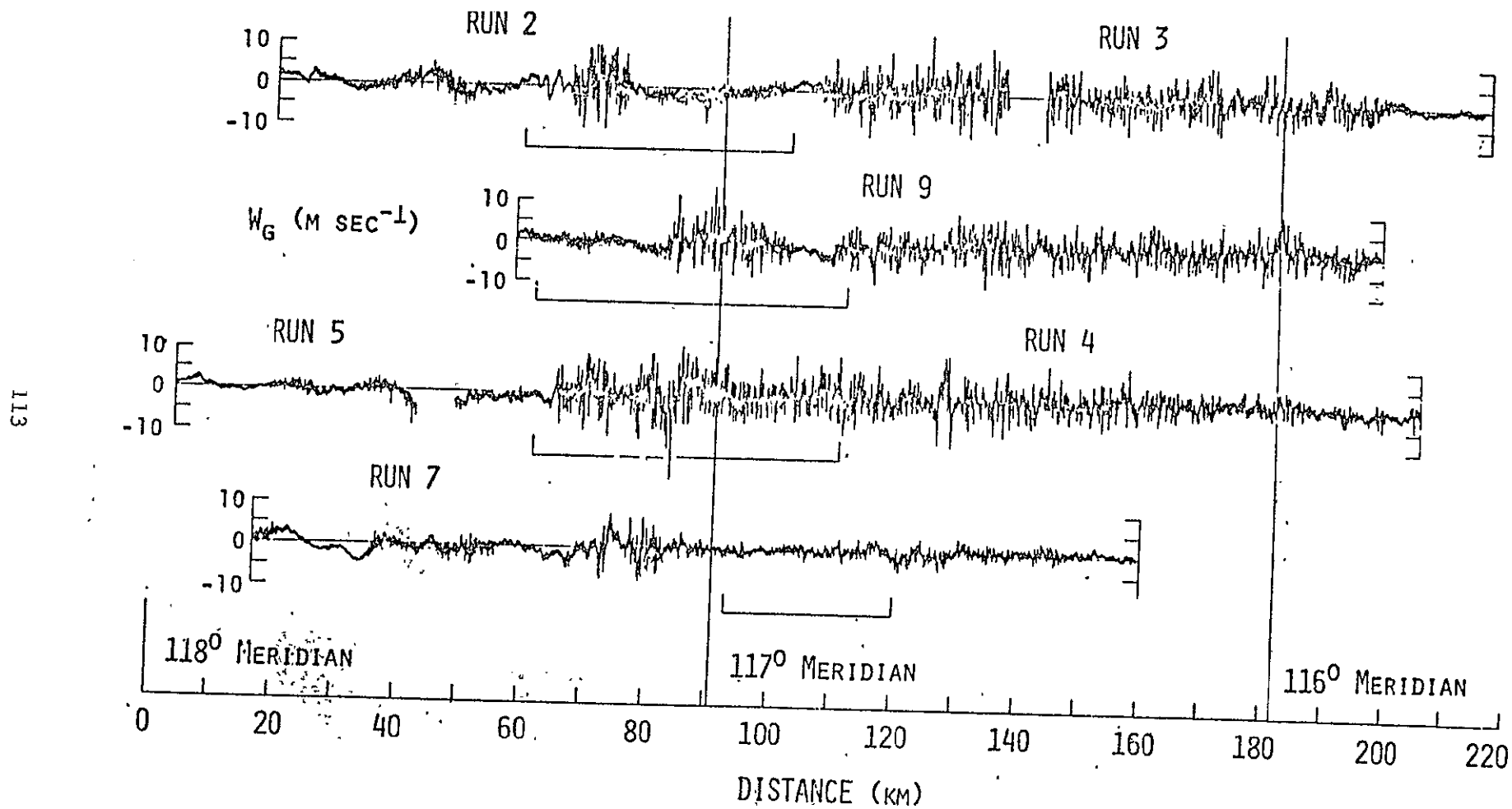


Figure C-57.- Time histories of vertical turbulence velocity (W_g) for all data runs on Flight 32. The meridians and the region of Death Valley below 1 km elevation (| |) are indicated.

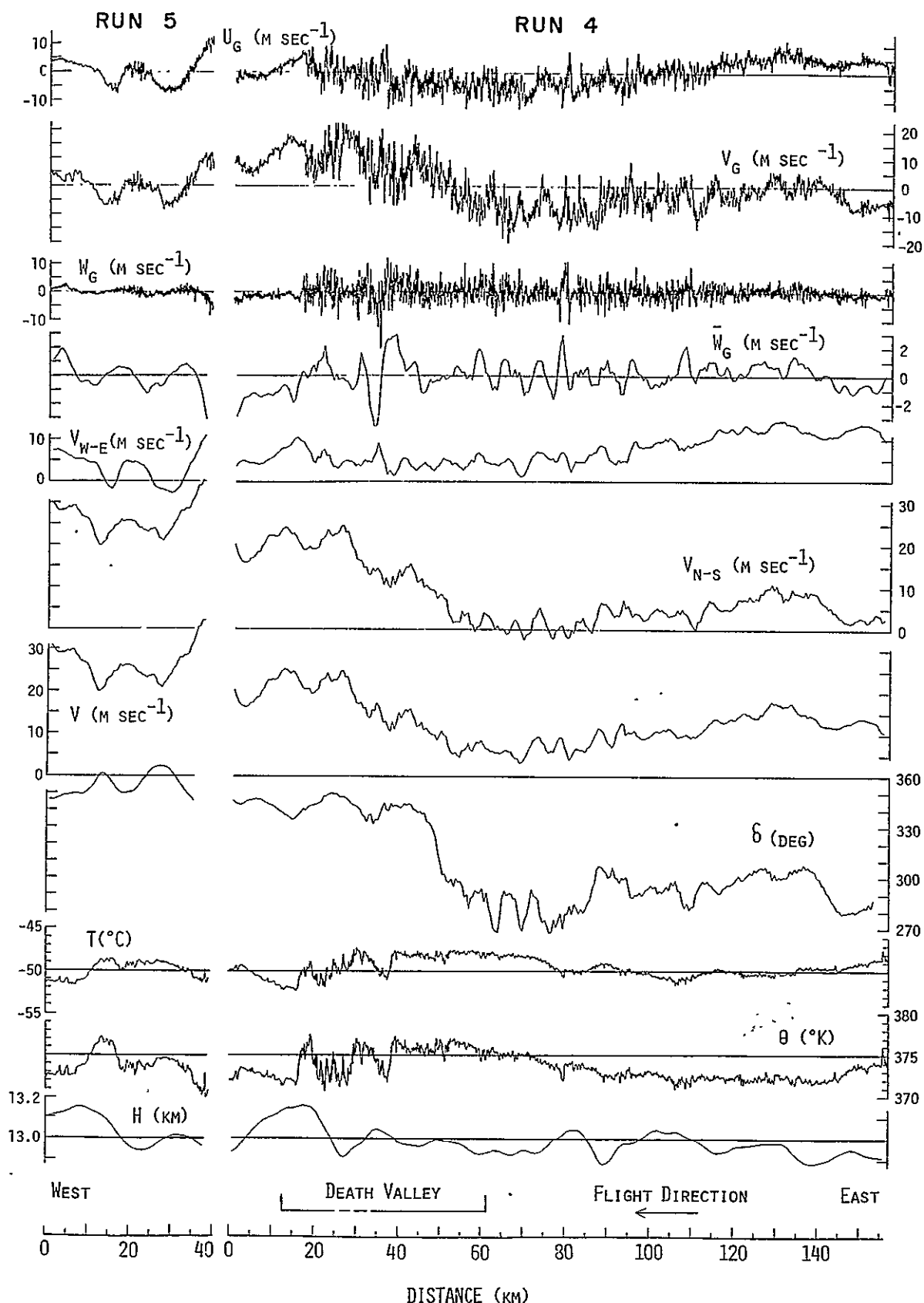


Figure C-58.- Time histories of longitudinal (U_g), lateral (V_g), vertical (W_g), and mean vertical (\bar{W}_g) turbulence velocities, west-east (V_{W-E}) and north-south (V_{N-S}) wind components, wind speed (V) and direction (δ), temperature (T), potential temperature (θ), and pressure altitude (H) for runs 4 and 5 of Flight 32. The region of Death Valley below 1 km elevation is indicated.

Table 1 have been applied to most of the quantities. Run 4 had continuous light or moderate turbulence for approximately 120 km. The three turbulence components show the increased activity in the imbedded zones. The two horizontal components also show large low frequency contributions related to changes in wind speed (lateral component) and direction (longitudinal component). Large horizontal shears in both wind speed and direction occurred above the eastern edge of Death Valley; the wind speed changed 18 m sec^{-1} in 27 km and direction changed 55 deg in 10 km within one of the zones on run 4. (The maximum wind shear values occurred in run 9 (changes of 13 m sec^{-1} and 40 deg in 7 km). The wind direction changed from 340° to 280° and back to 305° during run 4 (proceeding eastward). Wind speed was a minimum (5 to 8 m sec^{-1}) near the middle of the run where the wind direction was more westerly. A maximum speed of 20 to 25 m sec^{-1} occurred near the western extremes of run 4, increasing further westward to 35 m sec^{-1} on run 5.

The air temperatures recorded during all six data runs are plotted in figure C-59 as a function of the ground distance in the same manner as for figure C-57. The temperature plots show that warm regions were associated with the turbulence zones, which in turn were related to the areas above and to the east of the Death Valley depression. The close association between the warm regions and the turbulence zones is shown by comparison of the two sets of time histories in figures C-57 and C-59. Temperature fluctuations of 2°C to 3°C in less than 1 km occurred within the zone above Death Valley; outside of this region short period fluctuations were only 1°C or less. East of Death Valley long wavelength (15 to 25 km) temperature cycles were in phase with altitude variations, warmer zones coinciding with lower altitudes. An altitude increase of 150 m was generally accompanied by a temperature decrease of 1.5°C to 2°C ; hence, neutral to unstable conditions are suggested. The maximum temperature gradients was 4°C in 1.5 km on run 7.

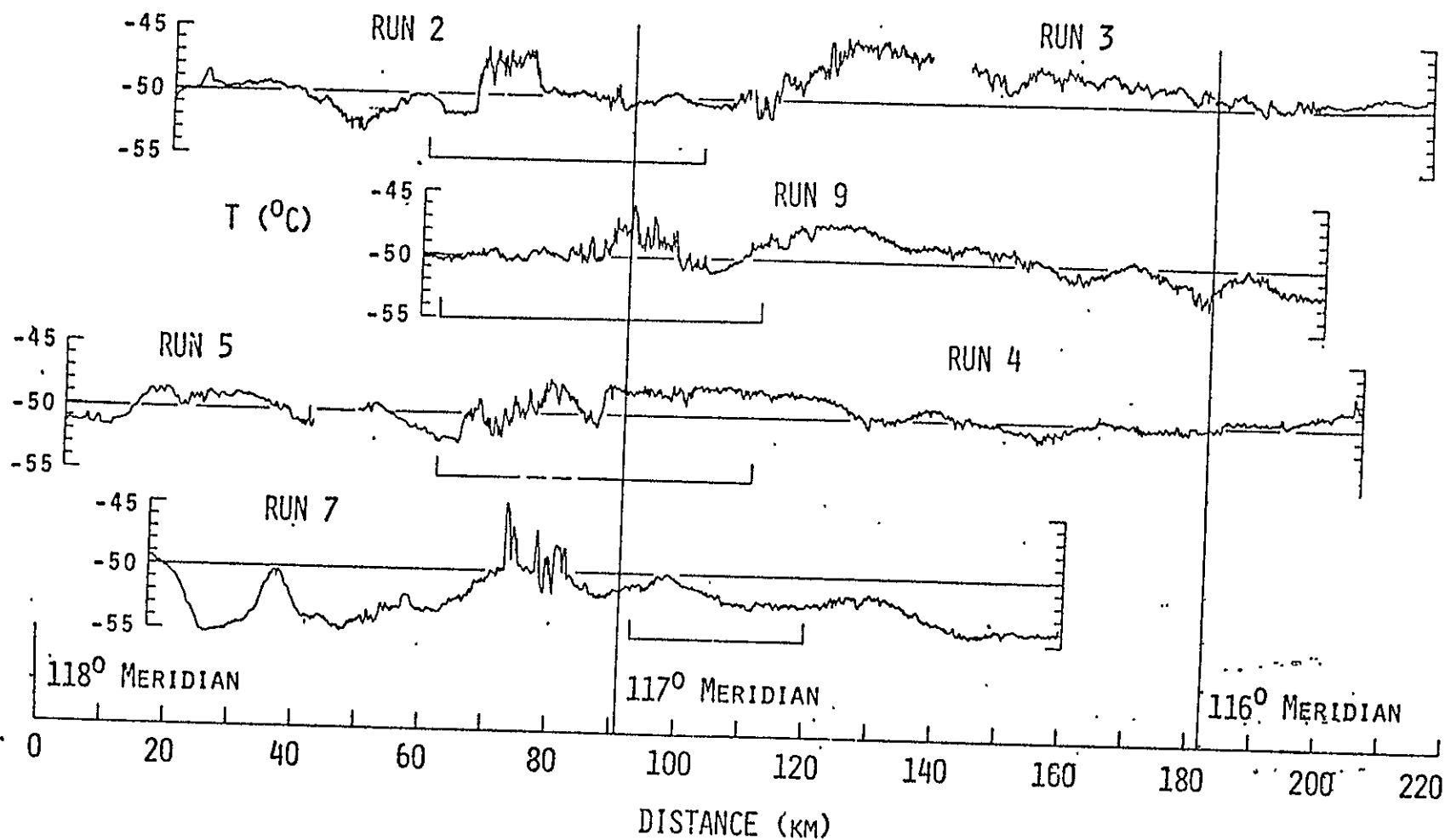


Figure C-59.-- Time histories of temperature for all data runs on Flight 32. The meridians and the region of Death Valley below 1 km elevation () are indicated.

The horizontal temperature field in the turbulence region at 13 km was constructed from aircraft data (fig. C-60). The time differences between the measurements (70 mins. at most) have been ignored in the construction. The horizontal temperature analysis shows warmer air to the north, with two warm tongues protruding southward. Each tongue was 10 to 20 km wide and generally aligned with the mountain ridges and valley depressions below. The more prominent tongue was associated with the Death Valley depression, following the valley contour in the northern part, but shifting to the western ridge as it progressed southward.

The tropopause sloped downward from west to east across the flight area (fig. C-55) and the wave-like mesoscale temperature variations (fig. C-59) may indicate that there were undulations on it. Since an intense inversion did not exist above the tropopause (and this flight was 1 km above it), the temperature changes in flight appear to have resulted largely from vertical air motions and to a lesser extent from aircraft altitude excursions.

The 100 to 350 m altitude variations of the aircraft during the data runs permitted construction of cross-sections of potential temperature (θ). These are shown in figure C-61, together with plots of the mean vertical turbulence velocity (\overline{W}_g), for the combination of runs 4 and 5 and for run 7, which showed the strongest wave action. Most noteworthy on the cross-sections are the large amplitude, wave-like features in the θ and \overline{W}_g histories, both with wavelengths of 15 to 25 km. The amplitudes of the oscillations in both θ and \overline{W}_g decreased from west to east, as did the θ gradients, which were especially large within the intense turbulence zone in the vicinity of Death Valley. The gradients were largest in run 7 over the ridge immediately to the west of Death Valley. Although the general flow during the sampling period appears to have

been nearly parallel to the main ridges of the Sierra Nevada and Inyo Mountains, which were west of the turbulence, significant changes in \bar{W}_g of 2 to 4 m sec⁻¹ with periods of 20 to 30 km occurred on runs 5 and 7. Changes in \bar{W}_g of ± 3 m sec⁻¹ occurred within the imbedded turbulence zone over and to the west of Death Valley on runs 4 and 7.

The turbulence on this flight, including the 10 to 20 km zone of moderate turbulence within the warm region associated with Death Valley, appears to have originated from breaking waves in flow over irregular terrain underlying a region of temperature and wind discontinuities. Waves and turbulence were triggered by shear interface surfaces that became intensified along the perimeter of a low velocity airstream. Breakdown of the waves into turbulence occurred when topographic effects influenced the relatively unstable airflow by increasing the vertical wind shear sufficiently to lower the Richardson number below the value of 0.25 that is critical for turbulence production. A favorable setting for turbulence was provided by the synoptic conditions: Large horizontal speed and direction shears in the southwest quadrant of an upper level trough (fig. C-56C), ^asteeply sloped tropopause, and large negative wind shears above the jet stream.

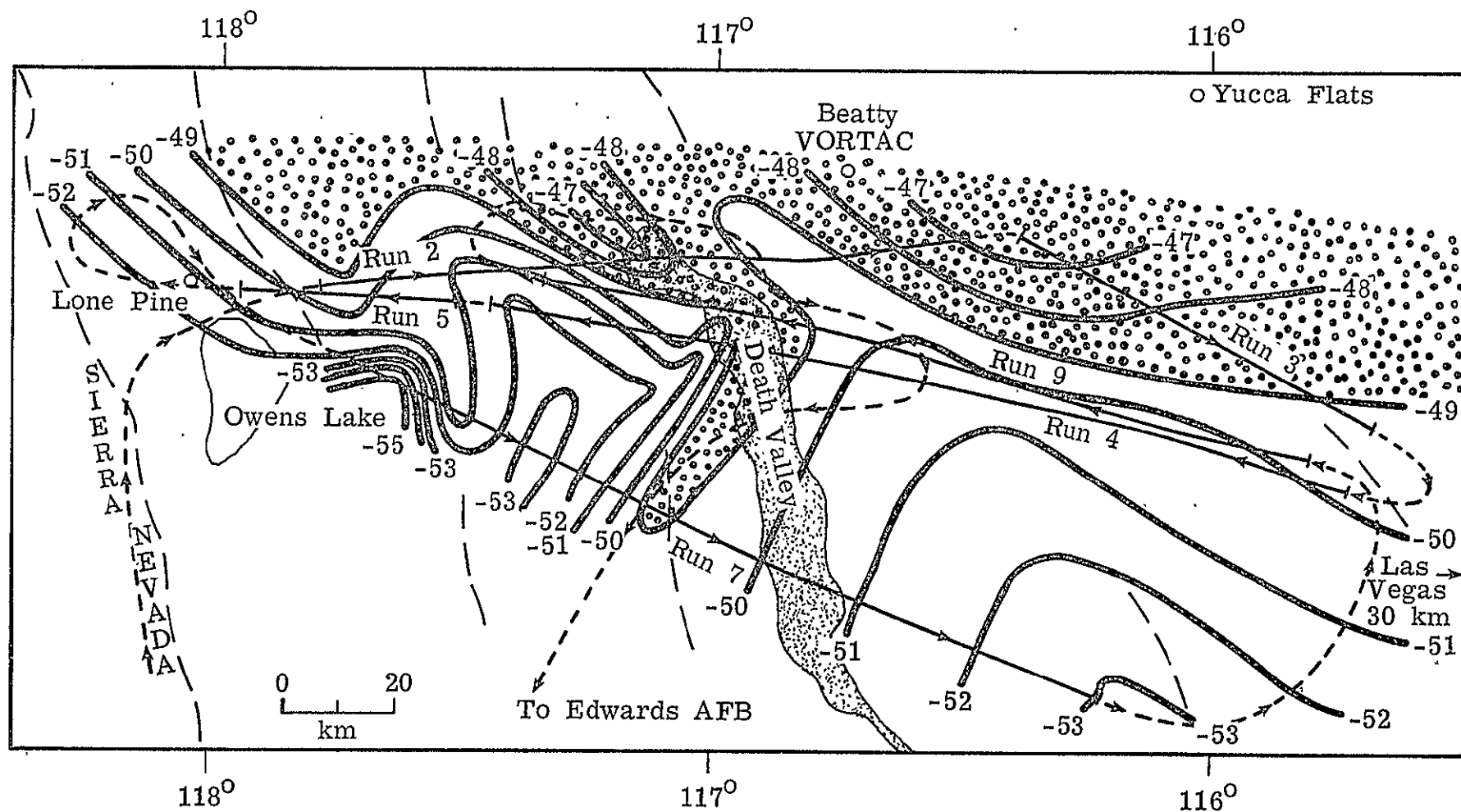


Figure C-60.- Horizontal temperature field at 13.0 km as derived from aircraft-measured temperatures. The area with temperatures above -49°C is dotted. The area of Death Valley below sea level and the mountain ridges above 2 km (---) are indicated.

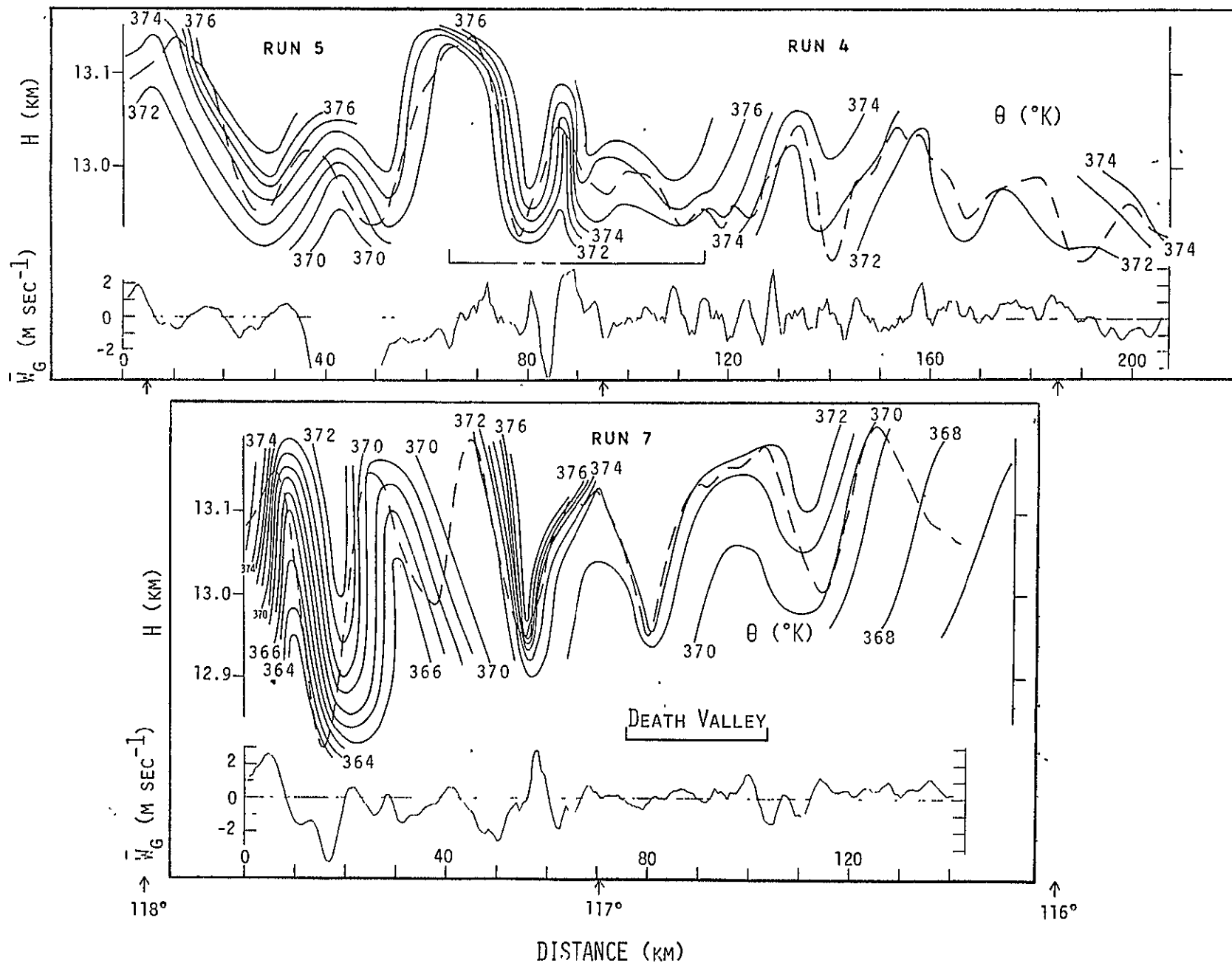


Figure C-61.— Potential temperature cross-sections and time histories of the mean vertical turbulence velocity (\bar{w}_g) for runs 4, 5, and 7 of Flight 32. The aircraft altitude (— — —) and the area of Death Valley below 1 km () are indicated.

Flight 33, March 28, 1975, 1147-1348 PDT (1847-2048 GMT)

Flight Summary

The purpose of this flight was to search for mountain wave turbulence south of the San Gabriel and Santa Suzanna ridges in southern California and for wind shear turbulence above the jet stream east of Edwards AFB. A NASA F-104 reported continuous light turbulence east of Edwards AFB at 14.0 km two hours prior to the B-57B takeoff. The first part of the plan was changed after receiving a pilot report of severe turbulence at 2.9 km over Desert Center, CA just before B-57B takeoff. Continuous light to moderate turbulence was sampled at 2.8 km for about 100 km on the approach to Desert Center through Banning Pass. The turbulence was orographic in nature and increased in intensity in the latter half of the run which was nearer the mountains. There was no significant turbulence above 1.8 km in the Desert Center area where a short run was taken in very light turbulence at 1.8 km. The B-57B climbed northwest from Blythe, CA, and, after a long delay due to ATC constraints, reached 14 km northwest of Hector, CA. Only small patches of very light turbulence were found in this region. Turbulence was noted below 3.4 km on climb and below 4.0 km on descent. Light to moderate turbulence occurred both on climb and descent near the Edwards area around 2.7 km.

Meteorological Conditions

At 1200 GMT, a moderately intense high in the northwest plus troughing along the California coast resulted in strong north-northeasterly surface winds throughout southern California. Sandberg, Calif., reported gusts to 21 m sec^{-1} and Ontario, Calif., 26 m sec^{-1} . Very cold air associated with the surface flow and supporting flow aloft had moved into southern California. The cold air

aloft was related to a slow moving northeast-southwestward-tilted trough. By 1800 GMT, temperatures in the Edwards AFB area had continued to decrease, especially below 3 km altitude. Winds in the lower levels were quite strong along the coast with Oakland reporting 29 m sec^{-1} at 2.7 km and Vandenberg AFB 37 m sec^{-1} at 3.7 km. Vertical wind shears were on the order of .020 to $.025 \text{ sec}^{-1}$ at these levels (and even stronger at Edwards where there was rapid change in the wind direction with height). The jet stream, with speeds up to 50 m sec^{-1} at inland stations, had its maximum strength along the California coast where wind data were lacking above 9.5 km. Significant horizontal shears existed east of Edwards AFB at high altitudes resulting from sharp changes in both wind speed and direction. Pilot reports of turbulence were numerous below but only occasional above 3.7 km.

Discussion

Strong wind velocities, nearly orthogonal to the ridges of the transverse (east-west) ranges, and large vertical wind shears created significant turbulence below 3 km in many areas of southern California. The region sampled probably was not representative of the most intense turbulence but was chosen because of active pilot reports therein. Continuous light turbulence at 14 km, sampled by a NASA F-104 prior to the B-57B flight, was **not** found, possibly because of a time lag or because the turbulent area was not directly searched due to ATC problems. Only a scattering of other pilot reports of turbulence existed above 3.7 km. Rapidly changing wind direction with height and a weak inversion at the tropopause were two possible reasons for the absence of extensive high altitude mountain wave turbulence.

Flight 34, April 4, 1975, 1150-1430 PDT (1850-2130 GMT)

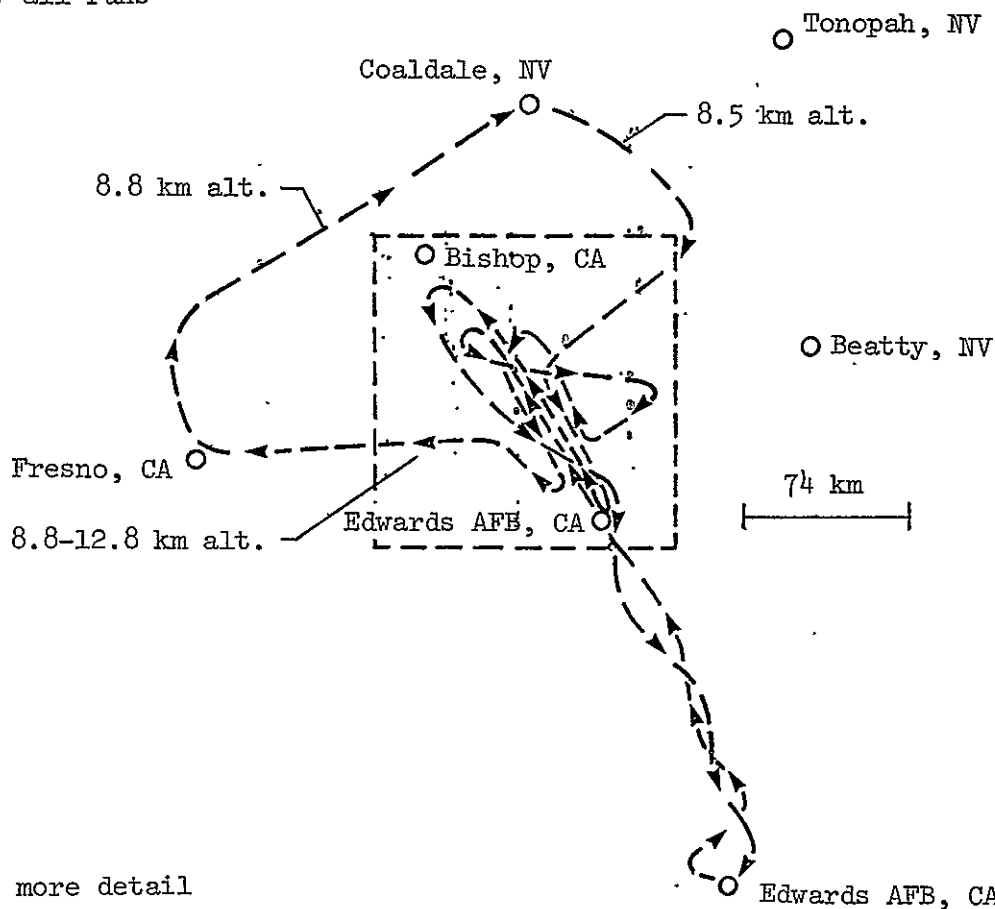
Flight Summary

The wind pattern, which consisted of strong flow at both low and high levels orthogonal to the main ridge, favored mountain wave turbulence east of the Sierra. A few reports of turbulence (intensity not reported) at 8.5 to 8.8 km were received 1 to 2 hours prior to the flight from commercial aircraft on the San Francisco-Denver airline route northeast of Bishop, CA. A NASA F-104, flying south of this area during the same period, reported extensive light turbulence at 12.8 km.

The B-57B took off with plans to search for mountain wave turbulence between the Owens Valley and Tonopah, NV in the altitude band of 8.5 to 12.8 km. Shortly thereafter a report was received from a NASA F-104 of severe turbulence at 4.3 km in the Owens Valley, north of Bishop, and light turbulence at 8.5 km to the northeast of Bishop. It was decided to investigate the severe turbulence area first. Two runs (2 and 3) were made south of Bishop in the Owens Valley at 4.4 km, the approximate altitude of the highest upwind peaks (fig. C-62). Turbulence was highly variable in intensity and quite severe at times with occasional smooth patches. These runs were within the rotor zone in clear air east of the Sierra. The turbulence was highly related to topography. The most severe jolts occurred leeward of the highest peaks. The two runs combined covered about 55 km.

After extensive delays due to ATC, the B-57B climbed to 12.8 km while enroute to Coaldale, NV, northeast of Bishop. There were several turbulence encounters, especially around 12.2 km, but all were brief

A. all runs



B. more detail

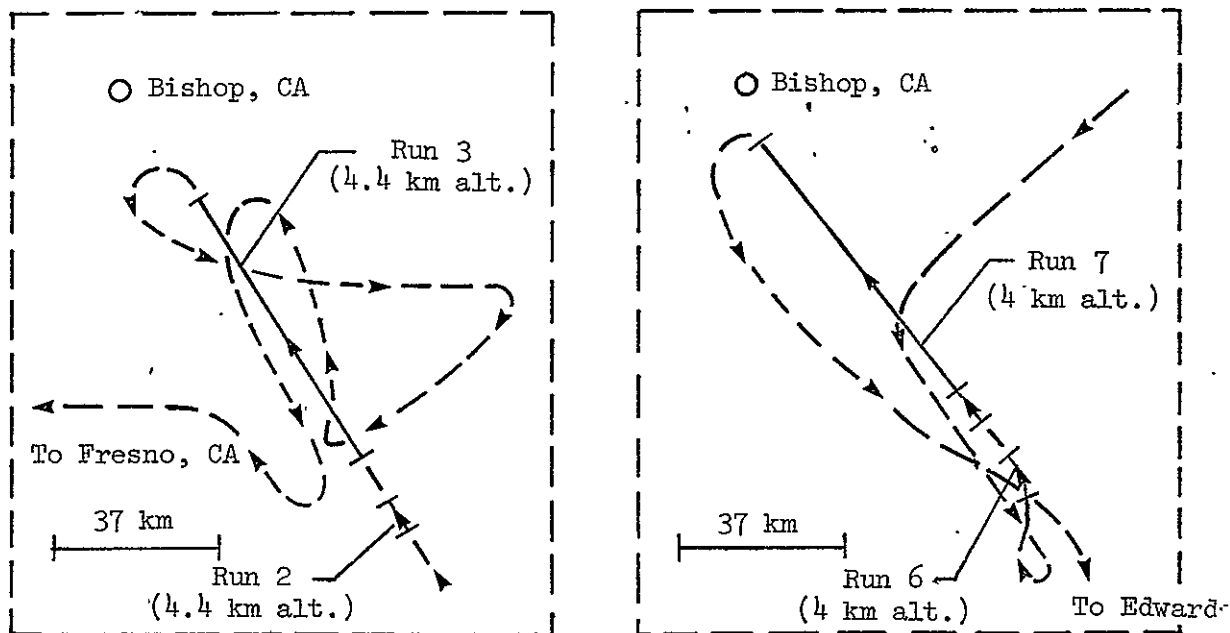


Figure C-62.- Composite of tracks for Flight 34, 1850-2130 GMT, April 4, 1975.

and only very light in intensity. Extensive searching was done between 8.5 and 8.8 km near the location of the earlier commercial airline turbulence reports but the results were negative. The B-57B then descended to the rotor zone in the Owens Valley where two moderately extensive runs (5 and 7) and one short run (6) were taken at 4.0 km in turbulence ranging up to extreme in intensity. Run 7 was nearly 90 km in length and mostly in severe to extreme turbulence. (Peak Δg excursions of 1g were equalled or exceeded 80 times!) Maximum incremental accelerations were +2.2 g and -1.8 g.

Meteorological Conditions

(a) Synoptic Situation. On the surface map at 1800 GMT (fig. C-63) there was a 1000 mb low in central Nevada and a 1005 mb low off the Oregon-Washington coast. The low pressure off the coast was situated under a deep trough system extending up to jet stream altitudes and oriented north-northwest to south-southeastward (see, e.g., the 700 mb and 500 mb maps in figures C-64 and C-65). The pressure dropped 13 mb across the Sierra between Fresno and Bishop at 1600 GMT (0800 PDT). Winds at ridge levels were from around 240° and between 15 and 21 m sec⁻¹ in central California at 1200 GMT and $250^{\circ}/23$ m sec⁻¹ at Slide Mountain near Reno, NV at 1600 GMT. At 500 mb, winds were from the same direction and between 33 and 41 m sec⁻¹ across the Sierra. The jet stream core was near the 300 mb level, and extended through central California to the northeast. Maximum speeds ranged from 51 to 62 m sec⁻¹. At 0000 GMT on April 5, 2 1/2 hours after the B-57B flight, low pressure was still present at the surface in eastern Nevada and a strong pressure gradient persisted across the Sierra.

Figure C-63.- Surface Analysis, 1800 GMT, April 4, 1975. Pressures in mb.

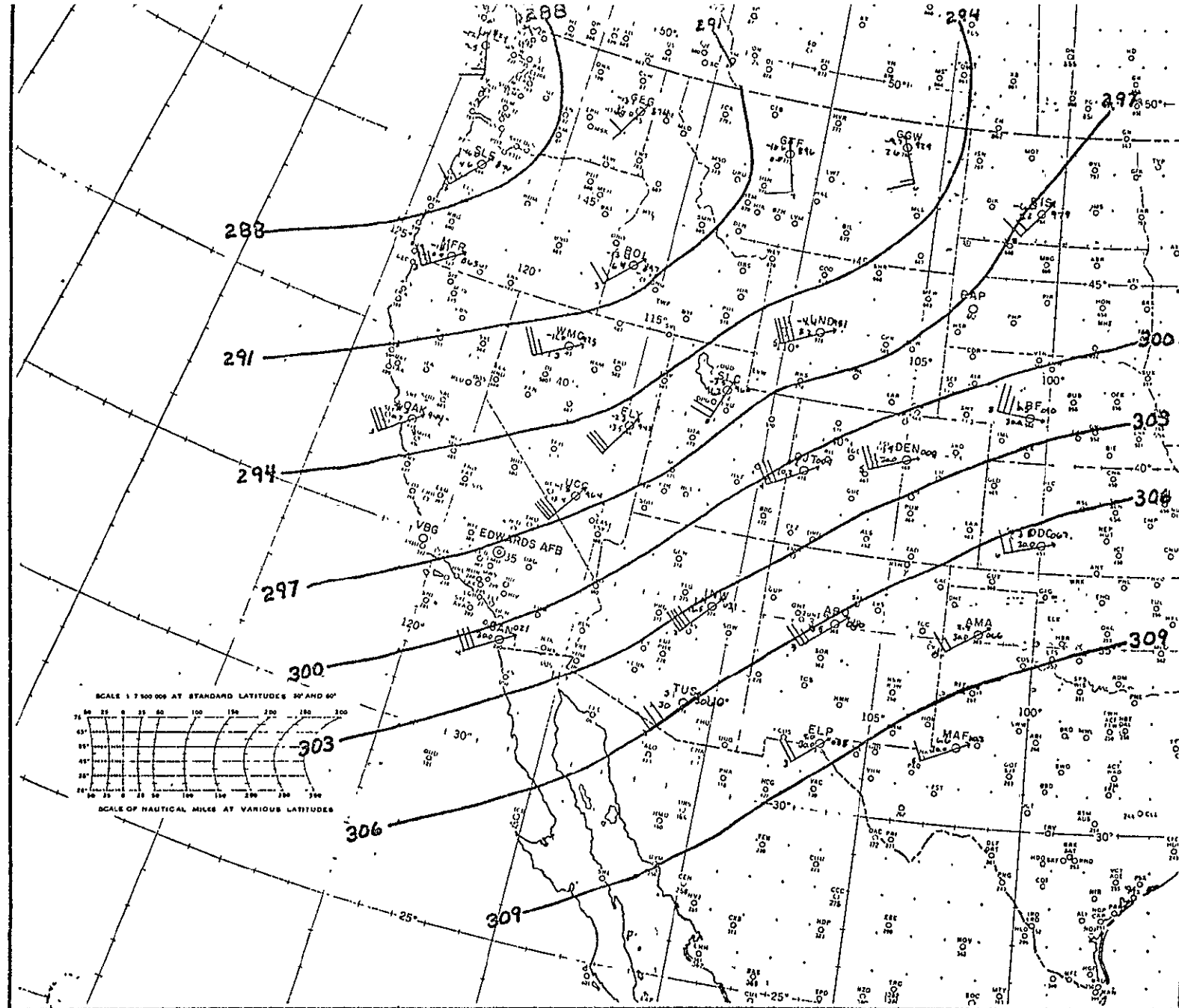


Figure C-64.- 700 mb Analysis, 1200 GMT, April 4, 1975. Heights in gpdam.

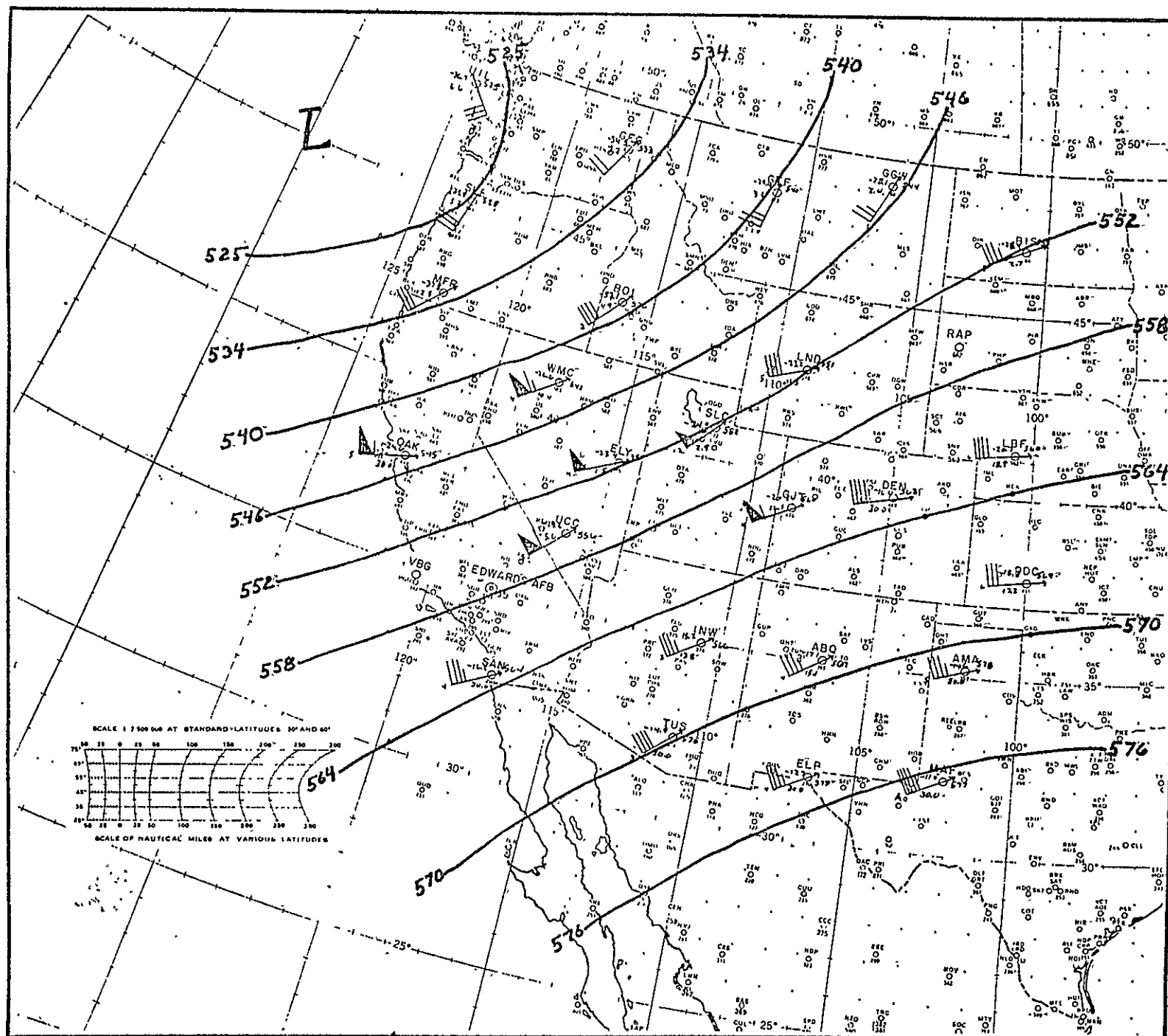


Figure C-65.- 500 mb Analysis, 1200 GMT, April 4, 1975. Heights in gpdam.

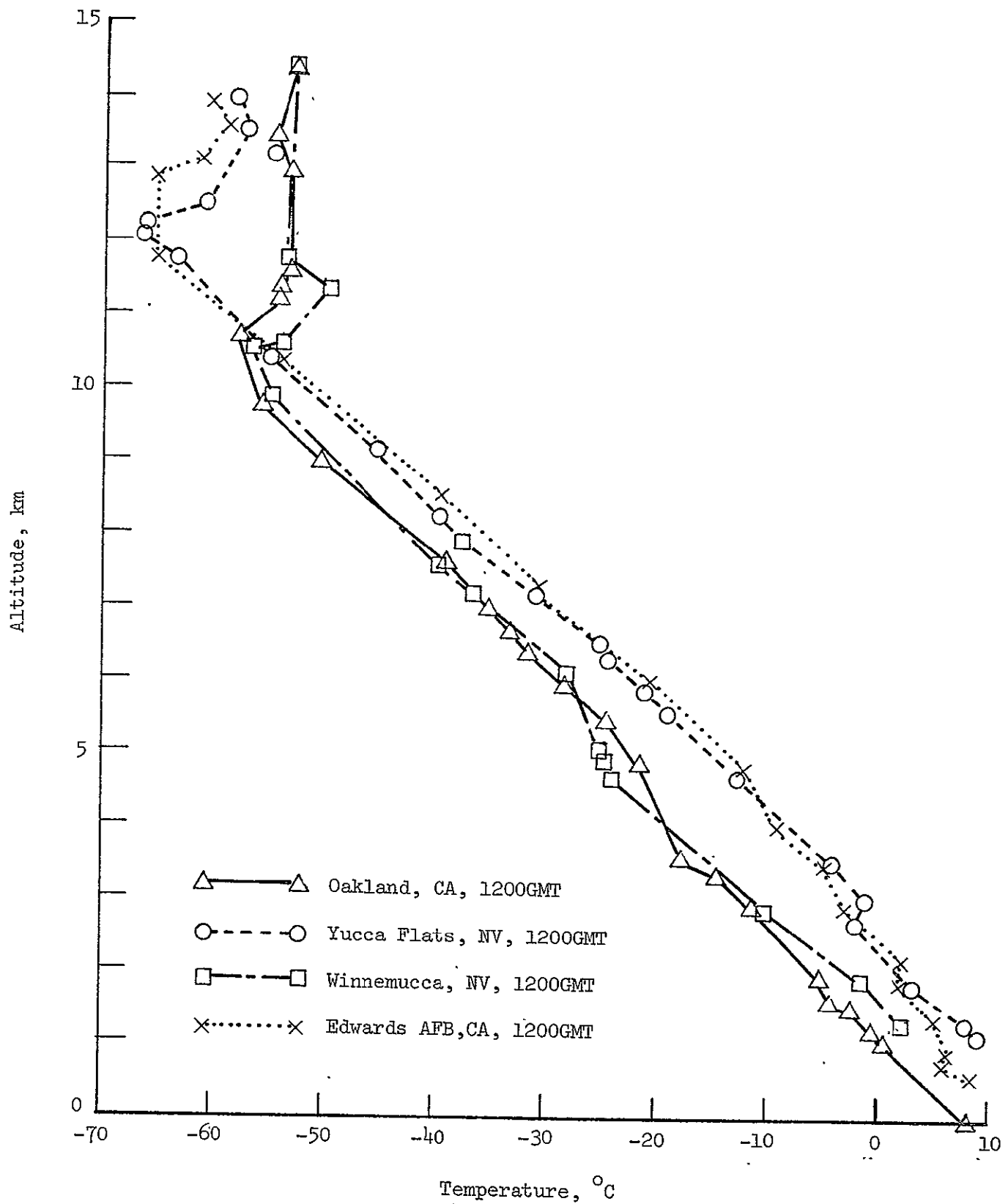


Figure C-66.- Rawinsonde temperature soundings for 1200 GMT, April 4, 1975.

The only significant changes in the 700 mb pattern consisted of the formation of a short wave trough in eastern California and a 5 m sec^{-1} decrease in wind speeds over Nevada. No major changes were noted at 500 mb or at jet stream levels.

(b) Rawinsonde Data. 1200 GMT soundings are shown in figure C-66 for Oakland, CA, and Winnemucca and Yucca Flats, NV, along with the 1000 GMT Edwards AFB RAOB. Colder air and a lower tropopause were present at the two northern stations. Characteristic features generally found during strong Sierra mountain wave situations, but which were absent on all soundings on this date, are: (1) an inversion near the height of the ridge level, (2) a strong tropopause inversion, and (3) an erratic temperature profile above the tropopause. Moderate negative vertical wind shears ($.017 \text{ sec}^{-1}$) were present above the tropopause at Yucca Flats and at Vandenberg AFB, CA in the morning and at Yucca Flats and Oakland at 0000 GMT. No significant shears were noted on either the 1200 GMT or 0000 GMT observations in central or northern Nevada, however. Oakland had very large shears, in excess of $.051 \text{ sec}^{-1}$ ($50 \text{ m sec}^{-1} \text{ km}^{-1}$) above 9 km, at 1200 GMT but the data appeared highly questionable because of the relatively low wind speeds in the layers above and below the level of maximum wind. Extensive cloudiness, a feature somewhat conducive to wave damping, existed over the Sierra during the flight. Rotor clouds, seen on figure C-67, were visible to the lee of the main Sierra ridge but they dissipated along a sharp line in the downslope flow. Hence, the turbulence runs were in clear air. Heavy haze was present in the Owens Valley and other valleys to the east and extended up to 5.5 km near Beatty, NV. A few lenticular clouds were observed in the northern Owens Valley and eastward between 4.6 and 6.1 km



Figure C-67.- Rotor Clouds in Lee of Sierra on Flight 34.



Figure C-68.- Lenticular Clouds in Owens Valley on Flight 34.

(fig. C-68). Extensive cirrostratus cloud covered the central Sierra at 8.8 km.

During run 7, two warm zones were noted. They were approximately 5 km long and had a temperature 4°C higher than the surrounding atmosphere. They appeared to coincide with a loss in altitude by the aircraft suggesting that they resulted from an increase in the downslope wind velocity. The wind speed varied over a range of 5 m sec^{-1} to 20 m sec^{-1} during the run, the lower speeds coinciding with zones of maximum turbulence intensity.

Discussion

Meteorological conditions were highly favorable for orographic turbulence in the rotor zone of the Sierra. Wind conditions also appeared conducive for extensive mountain wave activity and accompanying turbulence east of the Sierra. However, extensive cloudiness above the mountains may have inhibited the formation of a lee inversion near the ridge level. This inversion is important in the enhancement of the mountain wave amplitude which in turn increases the wind shear, eventually leading to wave breakdown and turbulence. The absence of a significant tropopause inversion had a similar adverse effect on the formation of high level mountain wave turbulence. Failure of the MAT aircraft to encounter turbulence in the area of previous pilot reports northeast of Bishop may have been largely due to holding pattern delays during changing meteorological conditions. The delays were caused by heavy airline traffic; the B-57B penetrated the high altitude region, where light turbulence had been reported by the NASA F-104 some 80 minutes before the penetration. The turbulence evidently changed considerably, both in intensity and areal coverage, during this short period.

Flight 35, April 5, 1975, 1053-1246 PDT (1753-1946 GMT)

Flight Summary

This flight, unusual in that it was flown on a weekend, was scheduled on the basis of a forecast made on the preceding day which called for mountain waves to form on the lee of the Sierra on Saturday. Although winds were favorable for wave activity on the morning of the flight, no pilot reports of turbulence were noted above 3 km. The B-57B flew along the lee of the Sierra and White Mountains to Coaldale, NV, and across central Nevada to Reno. The return flight leg was along the lee of the Sierra southeast of Lake Tahoe, across the White Mountains, and south to Edwards AFB on the east side of the Telescope Peak. Extensive searching was done between 10.7 and 13.7 km. A narrow zone of very light chop was encountered at 11.3 km, about a km above the sharp edge of a north-south oriented layer of cirrostratus clouds located 90 km southeast of Reno. Otherwise, the only turbulence observed was occasional very light patches above 6 km and light turbulence at 1.7 km on descent. No records were taken except on climbout.

Meteorological Summary

The surface map showed that much of the western United States was covered by low pressure at 1200 GMT. One large low, centered in north-western Nevada, affected the central California weather with extensive cloudiness and west-southwesterly winds across the Sierra and other ridges to the east. Cumulus tops extended to 3 km in the region around Edwards AFB and to 6 km over the Sierra Nevada. There was extensive light precipitation to the north and west of Edwards AFB at flight time and only a few breaks occurred in the overcast. Occasional shallow lenticular

clouds were observed imbedded in the cumulus at various altitudes below 6 km. There were multiple cirrus layers, generally below 10.7 km. The upper level flow was dominated by a deep trough centered off the California coast. Southwest flow was prevalent at all levels with speeds in the Sierra region ranging from 13 to 15 m sec⁻¹ at ridge level, 26 to 35 m sec⁻¹ at 4.3 km, and 46 to 50 m sec⁻¹ from 6 to 9 km. The trough was migrating slowly southeastward and very cold air was being advected into central California below 6 km at flight time. At 1200 GMT the tropopause height at Oakland was only 6.4 km, or 5.0 km lower than at Vandenberg AFB, CA and Yucca Flats, NV. Vertical wind shears of .020 sec⁻¹ and larger occurred at various levels above 6 km at Oakland, CA and Winnemucca and Yucca Flats, NV. There were no pronounced inversions at any station, either at ridge levels or above.

Discussion

Although wind speeds and directions appeared favorable for Sierra mountain waves, a large influx of moisture and cold air below 6 km reduced the wave activity to shallow layers. Absence of temperature inversions and frontal passages and the slow progression of the upper air trough were also instrumental in adversely affecting wave production.

Flight 36, April 14, 1975, 1207-1341 PDT (1907-2041 GMT)

Flight Summary

A Boeing 727 reported moderate turbulence at 12 km over Reno, NV in the early morning. Standing lenticular clouds were observed at the Reno weather station at the same time. Also, a NASA F-104 found persistent light to light-moderate turbulence and wave action east of Lone Pine, CA, at 12 km, 1 1/2 hours before the B-57B takeoff. Based on these reports and favorable wind conditions, plans were initiated to fly a mountain wave pattern east of the Sierra around Lone Pine. After a disappointing search in this area the B-57B descended towards Edwards AFB and searched the Antelope Valley--Mojave Desert region between 5.5 and 6.1 km. Some brief patches of light turbulence were encountered north of Edwards AFB near 6 km but were of insufficient length to warrant records. Moderate turbulence was present below 1.2 km on both climbout and descent. One run was taken in patchy, very light turbulence at 11.9 km east of the Sierra.

Meteorological Conditions

A weak cold front extended from a low pressure center in southwestern Idaho into central California at 1200 GMT. The front had advanced to near Edwards AFB at flight time. Concurrently, there was a pressure drop of 11 mb between Fresno and Bishop, CA. A broad trough at 500 mb, located along the Pacific coast at 1200 GMT, had divergent flow in central and southern California. Winds were from the west-southwest at all levels, as high as 23 m sec^{-1} along the ridges of the Sierra but not much stronger at 500 mb. Jet stream winds in this area were 45 to 50 m sec^{-1} . Moderate negative wind shear of $.019 \text{ sec}^{-1}$ existed above the jet stream at Ely, NV and

Vandenberg, CA. Oakland had a shear of $.029 \text{ sec}^{-1}$ between 6.1 and 6.7 km. Winds increased considerably and became more southerly at upper levels in the 12 hours following 1200 GMT as the cutoff low off the Washington coast deepened and moved slowly southward.

Cloud cover during the flight was extensive, especially over the Sierra and to a lesser extent over the ridges to the east. Valleys were generally cloud-free. There were wave clouds observed as high as 8.8 km, mostly well east and southeast of the Sierra. The general cloud cover was noted to have increased considerably in the two hours between the NASA F-104 flight east of the Sierra and the B-57B search. During the run east of Long Pine temperature fluctuations of $+3^{\circ}\text{C}$ were noted as well as moderate excursions in airspeed and altitude suggesting the presence of wave activity. A sawtooth pattern observed in the B-57B temperature sounding above 12.5 km may have been indicative of mountain waves.

Discussion

Clouds associated with a frontal system moving through the flight area seem to have been related to the reduction of wave turbulence in the Sierra region. The turbulence reported in the period immediately prior to the B-57B flight may have been associated with a surface frontal passage.

Flight 37, April 17, 1975, 1144-1301 PDT (1844-2001 GMT)

Flight Summary

The flight plan was to search for turbulence in a zone of strong vertical wind shear near 6 km above Blythe, CA. Shortly after takeoff the course was changed due to a commercial pilot report of turbulence (intensity unspecified) between 6.1 and 7.0 km, 37 km northeast of Hector, CA. The R-57B proceeded to Hector and on to Boulder City, NV, searching between 5.8 and 7.3 km. Only intermittent patches of turbulence were found, during a run just above cirrostratus cloud at 6.4 km, northeast of Hector. The top of the cirrostratus deck rose above 6.4 km near Boulder City where some light-moderate turbulence was encountered just below the cloud tops. On the return to Edwards AFB, searching took place up to 12.5 km. Again, only scattered patches of very light turbulence were noted. Some moderate turbulence existed at 2.7 km and below on descent whereas only light-moderate turbulence was encountered on climbout, below 1.4 km.

Meteorological Conditions

At the surface an extensive, nearly stationary, low pressure system centered in Nebraska covered a large portion of the U.S. at 1200 GMT. Fairly weak northwesterly flow existed in southern California on the back side of the low. The winds in this area were expected to increase during the afternoon as the low deepened and pressures rose along the northwestern U.S. Coast. The 500 mb chart showed a deep northeast - southwestward oriented trough extending into southern California resulting in very cold air advection below 6 km. This was reflected in the low tropopause heights, e.g., 6 km at Edwards AFB. Relatively weak winds

existed near the center of the 500 mb low but increased rapidly outward. Along the southern and eastern sides of the low rather large vertical wind shears were present between the layer with moderately weak winds near 500 mb and the overlying jet stream. Edwards AFB and San Diego, CA and Yucca Flats, NV all reported shears of at least $.025 \text{ sec}^{-1}$ centered around 6 km. The zone of large vertical shears was expected to move towards the Blythe area as the low progressed east-southeastward. There was a negative shear of $.029 \text{ sec}^{-1}$ at Edwards AFB above the jet stream. Extensive cumulus buildups existed in the flight area; these flattened out at the tropopause (near 6.7 km) where wide layers of cirrostratus were formed. Several wave clouds were observed at lower altitudes east of Edwards AFB.

Discussion

The failure to find significant turbulence in the shear zone may have resulted from the rapid progression of the upper air low eastward. Winds measured on the run northeast of Hector were only 16 m sec^{-1} suggesting that this area was within the weak wind zone of the low center and lay to the northwest of the zone with the largest shears. There was a general absence of turbulence reports by pilots except for one report at 2000 GMT of smooth air at 6.4 km between Blythe, CA and Yuma, AZ. This leads to the speculation that perhaps there was no large area of significant turbulence within the zone containing the large shears.

Flight Summary

Meteorological conditions on the morning of the flight were borderline for the formation of mountain waves of sufficient strength to produce turbulence. Two reports of turbulence were received from NASA aircraft in the early afternoon, however; both at 11.6 km and east of the Sierra (a YF-12 reported light to light-moderate turbulence on descent north of Owens Lake and an F-104 encountered continuous light turbulence in this area and also between Bishop, CA, and Coaldale, NV). The B-57B searched to 11.6 km in the Owens Valley. Light turbulence was noted on climbout below 1.2 km and very light chop at various altitudes up to 9.8 km. No turbulence existed at 11.6 km in the vicinity of the earlier pilot reports. Air Traffic Control then suggested that searching be extended to northeast of Coaldale (Figure C-69) between 10.7 and 11.6 km where an airline pilot had reported turbulence. Only very light intermittent turbulence was found on run 3 northeast of Coaldale at 11.6 km. On run 5, however, a 5.5 km encounter with light turbulence occurred at an altitude of 10.7 km and 17 km leeward of an isolated peak. The location was 65 km northeast of Coaldale. Run 6, which was also at 10.7 km (as were runs 7 and 8), was taken on a reciprocal track to that of run 5, (i.e. northeastward, instead of southwestward). Turbulence was generally intermittent and very light except for a 5.5 km patch of light turbulence northeast of Coaldale. The turbulence lay 11 km to the lee of a high ridge. On run 7, taken on a northwestward track orthogonal to run 6, 11 km of light to light-moderate turbulence was recorded at a location 20 km eastward (leeward) of a 3 km ridge. The rest of the run had only patchy very light turbulence. Run 8's south-southwestward heading followed a course parallel to and 13 km leeward

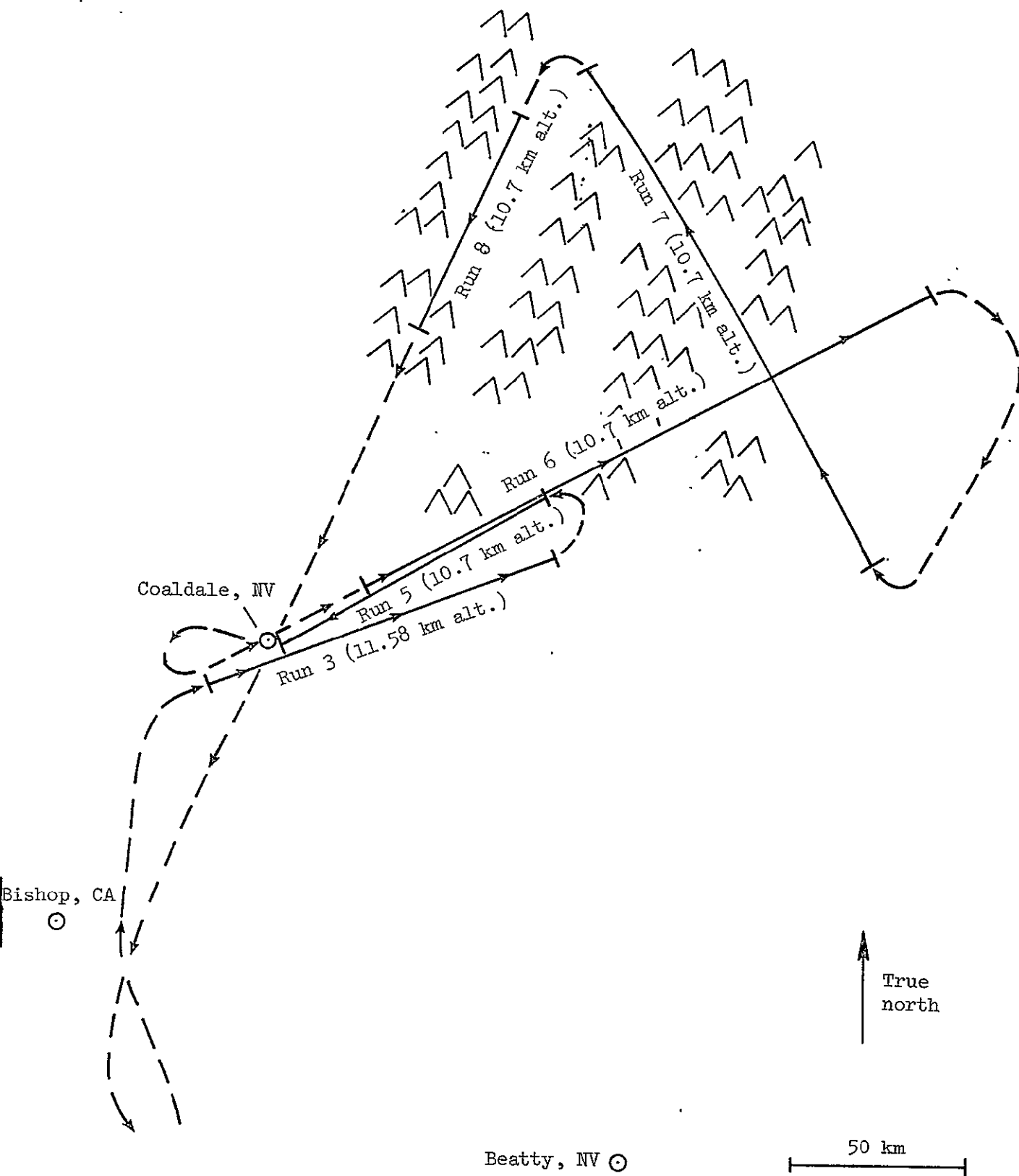


Figure C-69.- Track for Flight 38, 2210-0054 GMT, April 24-25, 1975.

of a ridge with peaks over 3.4 km; surprisingly no turbulence was encountered. Several patches of very light turbulence were noted on descent at various altitudes. Light turbulence was found at 2.9 km, moderate turbulence at 2.1 km, and light turbulence below this altitude. Only a scattering of commercial and military aircraft turbulence reports were received in California and Nevada above 3 km on the day of this flight.

Meteorological Conditions

Synoptic situation.- The 1200 GMT weather pattern did not present an especially encouraging picture for mountain wave turbulence. A weak high was located in southwestern Wyoming and only a 5 mb pressure drop existed across the Sierra. An occluded front was advancing towards the coast of northern California. 700 mb winds were generally less than 10 m sec^{-1} in California and Nevada and divergent flow across the Sierra at 500 mb produced only slightly higher speeds. Jet stream winds were westerly in central California with speeds of 35 to 40 m sec^{-1} . An upper air low centered 460 km off the British Columbia coast was forecasted to move southeastward, thereby tightening the pressure gradient over California. Surface winds were also expected to increase across the Sierra as the pressure lowered on its leeward side. By 1500 GMT Slide Mountain near Reno, NV, reported gusts of 20 m sec^{-1} from the west-southwest. A special 2100 GMT Edwards RAOB showed west-northwest winds of 17 m sec^{-1} at 3 km.

A surface low had become well developed in eastern Nevada by 0000 GMT on the 25th, causing an increase in the pressure gradient across the Sierra. 700 mb winds over California and western Nevada were generally from the southwest and ranged between 13 and 20 m sec^{-1} . The broad trough was

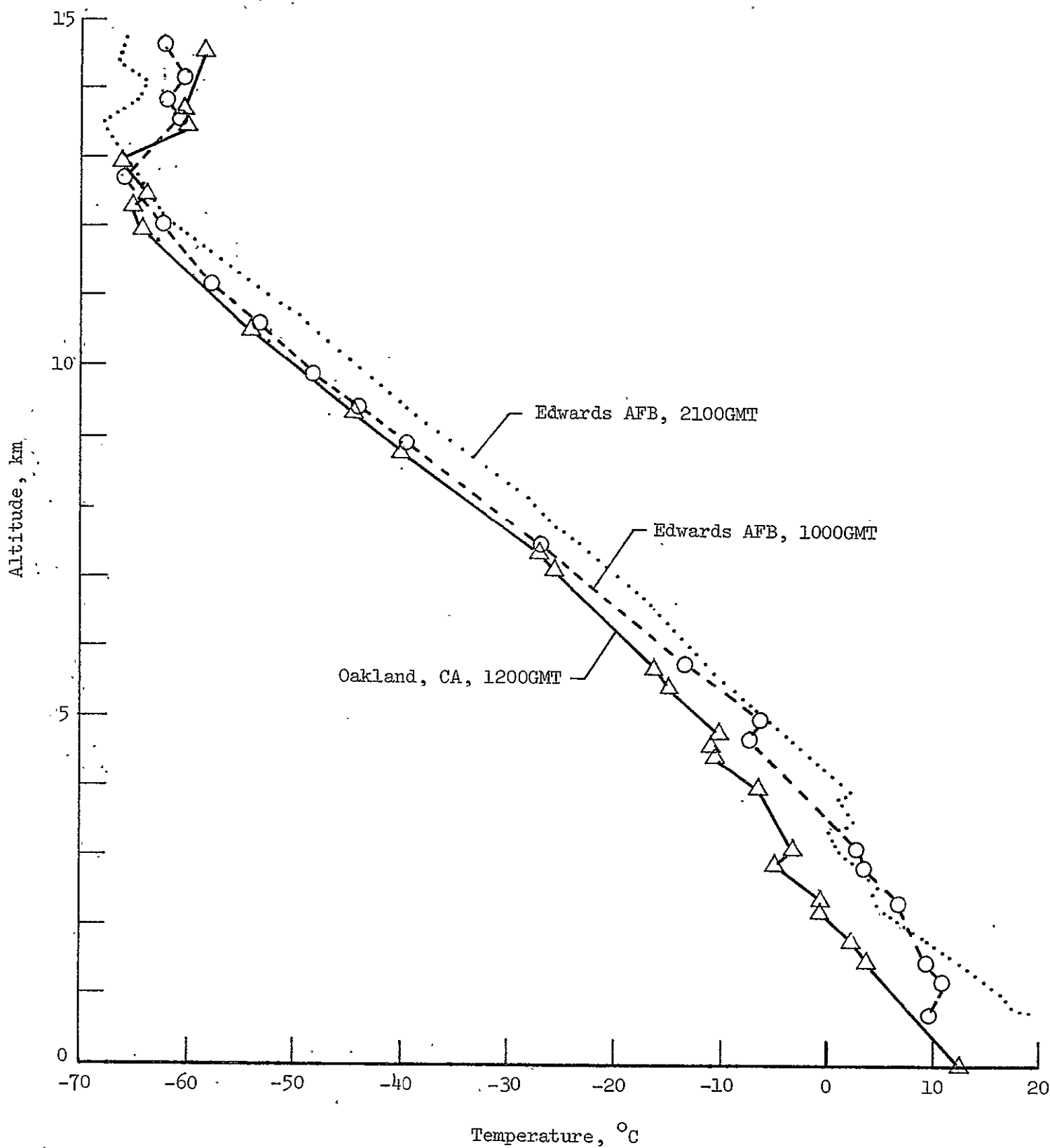


Figure C-70.- Rawinsonde temperature soundings on April 24, 1975 for Oakland and Edwards AFB, Calif.

maintained at 500 mb but movement of its low center southeastward tightened the gradient over both California and Nevada, resulting in 10 to 15 m sec⁻¹ wind speed increases. The jet core remained in central California and Nevada with west-southwest winds of 45 m sec⁻¹ and greater at 250 mb.

Rawinsonde data.- Below 6 km the 1200 GMT temperatures at Oakland were lower than had existed 2 hours previously at Edwards AFB (figure C-70). Oakland's tropopause was only slightly below that of Edwards, however. A special 2100 GMT RAOB at Edwards (figure C-70) showed that warming had taken place at nearly all levels up to the tropopause in the previous 11 hours. A moderate inversion had also developed near 3 km. Some cooling occurred near this level at Oakland during approximately the same period and a fairly deep stable layer had formed above 3.7 km by 0000 GMT. Vertical wind shears calculated from morning balloon releases at Oakland and Edwards AFB were 0.12 sec⁻¹ or less at all levels. A shear layer of .017 sec⁻¹ existed at Ely, NV, below the jet stream and one of -.022 sec⁻¹ at Medford, OR, above the jet stream, both centered near 10.7 km. Small shears persisted at Edwards AFB by 2100 GMT. Oakland, however, had 3 layers with shears greater than .022 sec⁻¹ between 11.0 and 13.7 km at 0000 GMT.

Clouds.- Overcast conditions prevailed over much of northern and central California during the flight, especially over the mountains. These clouds were mid-altitude type with tops up to 4.6 km over the Sierra. Cirrostratus cloud layers were noted above 12.2 km north of the flight area. Waveform clouds existed over and leeward of the southern Sierra and Tehachapis at around 3 km, but none were observed eastward of the central Sierra except for suggestions of light wave activity in cirrus clouds at 11.3 km.

Discussion

The B-57B failed to locate a zone of light turbulence eastward of the Sierra near the tropopause, reported only 1 to 3 hours earlier by two NASA aircraft. The discontinuous nature and rapid disappearance of the turbulence suggests that wind shear associated with a migrating short wave system was the prevailing force, rather than mountain waves, in causing the turbulence. The relatively brief patches of light to light-moderate turbulence encountered by the B-57B apparently were connected with orographically-induced flow although no strong mountain waves were evident. Lack of turbulence leeward of some of the more prominent ridges suggested that the causes of the disturbances were limited to local regions.

Flight 39, May 20, 1975, 1113-1326 PDT (1813-2026 GMT)

Flight Summary

Weather observations indicated that conditions were favorable for mountain wave turbulence leeward of the Tehachapi range. Several pilot reports of turbulence below 4.6 km altitude, including one from a NASA F104, confirmed the forecast. The F-104 also encountered continuous light turbulence north of Edwards AFB at altitudes between 12.2 and 12.8 km. Therefore, it was decided the situation warranted two flights of the MAT B-57B, one flight in the morning below 4.6 km altitude, and another in the afternoon at higher altitudes.

Flight 39, the morning flight, departed at 1113 PDT and proceeded to the Tehachapis. Run 2 (figure C-71) was made heading into the flow leeward or southeast of the ridge at 3.2 km, the altitude where moderate turbulence had been encountered on climbout. This run was terminated after nearly six minutes because of heavy cloudiness at the flight level. After a short climb to top the clouds, the aircraft proceeded back towards the Tehachapis at 4.2 km, encountering light and occasionally moderate turbulence for about four minutes on Run 3. The turbulence, varying continuously in intensity, ended abruptly just short of the mountains, the cessation coinciding with a clear area below. After a course reversal, Run 5 was made heading southeastward through almost 10 minutes of light to occasionally moderate turbulence with imbedded smooth patches. The smooth areas again coincided with clear areas below. On one occasion it was noted that the heavier turbulence occurred in a wave trough. Some fairly rapid temperature changes, up to 4°C amplitude, were observed; the total change

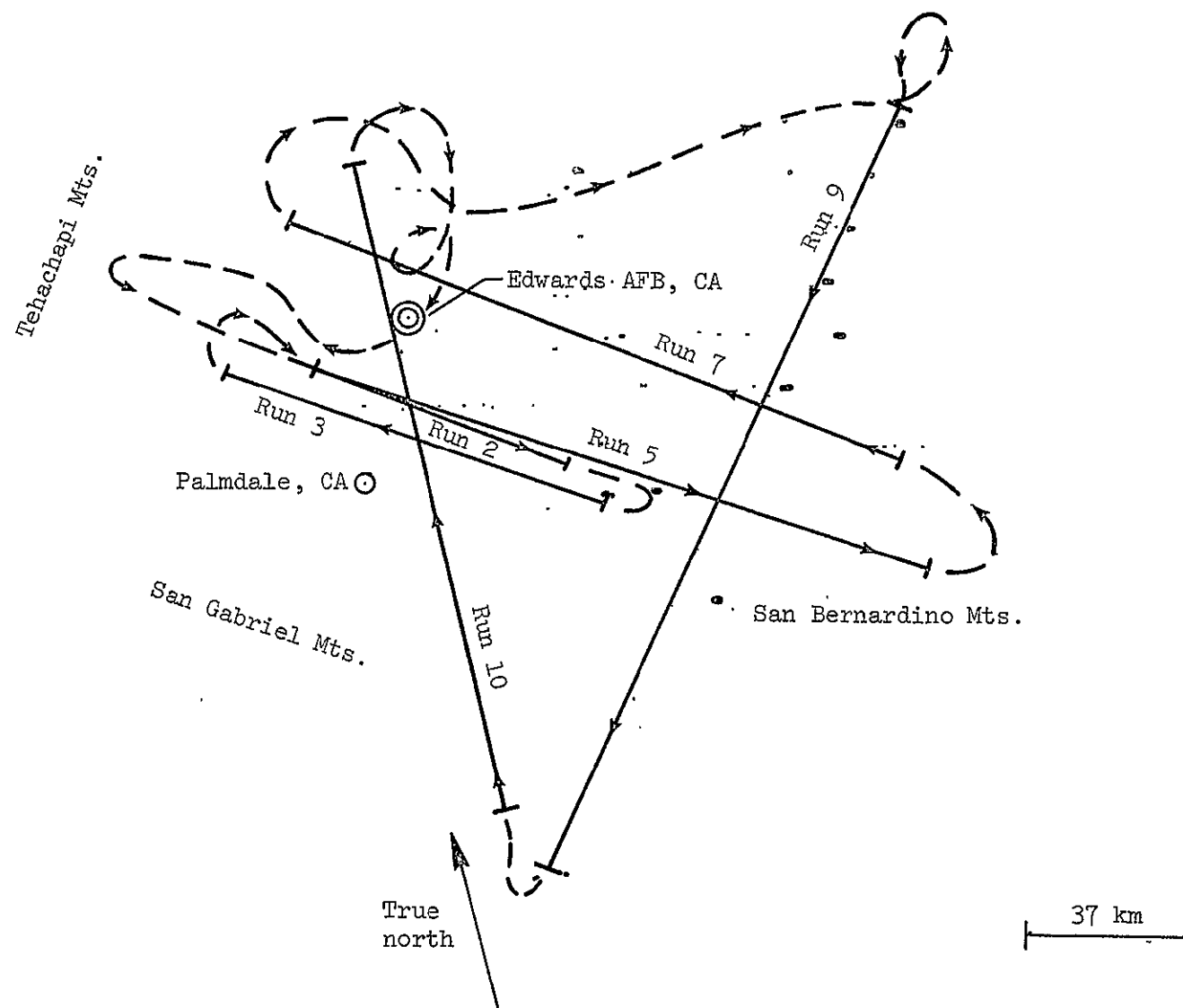


Figure C-71.- Track for Flight 39, 1813-2026GMT, May 20, 1975. See narrative for altitudes.

during the run was 9°C . On Run 7, the aircraft again approached the ridge from leeward. This run was nearly parallel to Run 5, and displaced about 27 km northeastward from it. The turbulence, with imbedded smooth patches lasted almost 14 minutes, with intensity and intermittency similar to that observed on Run 5. The temperature and airspeed fluctuations observed supported the existence of mountain waves (fig. C-72). Temperature changed 15°C across the run. Run 9 had a southwesterly heading, perpendicular to the previous runs. Turbulence near the start of this run was generally light or less, increasing to moderate and occasionally severe towards the latter part of the run. The run included a period of continuous turbulence of varying intensity lasting seven minutes. Approximately one minute of severe turbulence was encountered just south of the ridge line of the San Gabriel mountains, including an extreme gust with an incremental acceleration of -2.5 g . Such severe turbulence was unexpected, because the winds were nearly parallel to the ridge line. During the run a 10°C temperature change in less than one minute, and a total temperature change of 13°C were noted (fig. C-73). The final turbulence run (No. 10) was taken on a northerly heading at an angle oblique to both the Tehachapi and San Gabriel ridge lines. Severe turbulence was again encountered south of the San Gabriels, followed by light turbulence or less during the remainder of the run.

Meteorological Summary

On the morning of the flight, surface winds blew from the northwest (cross-ridge) at Tehachapi, gusting to 21 m sec^{-1} . The Edwards winds

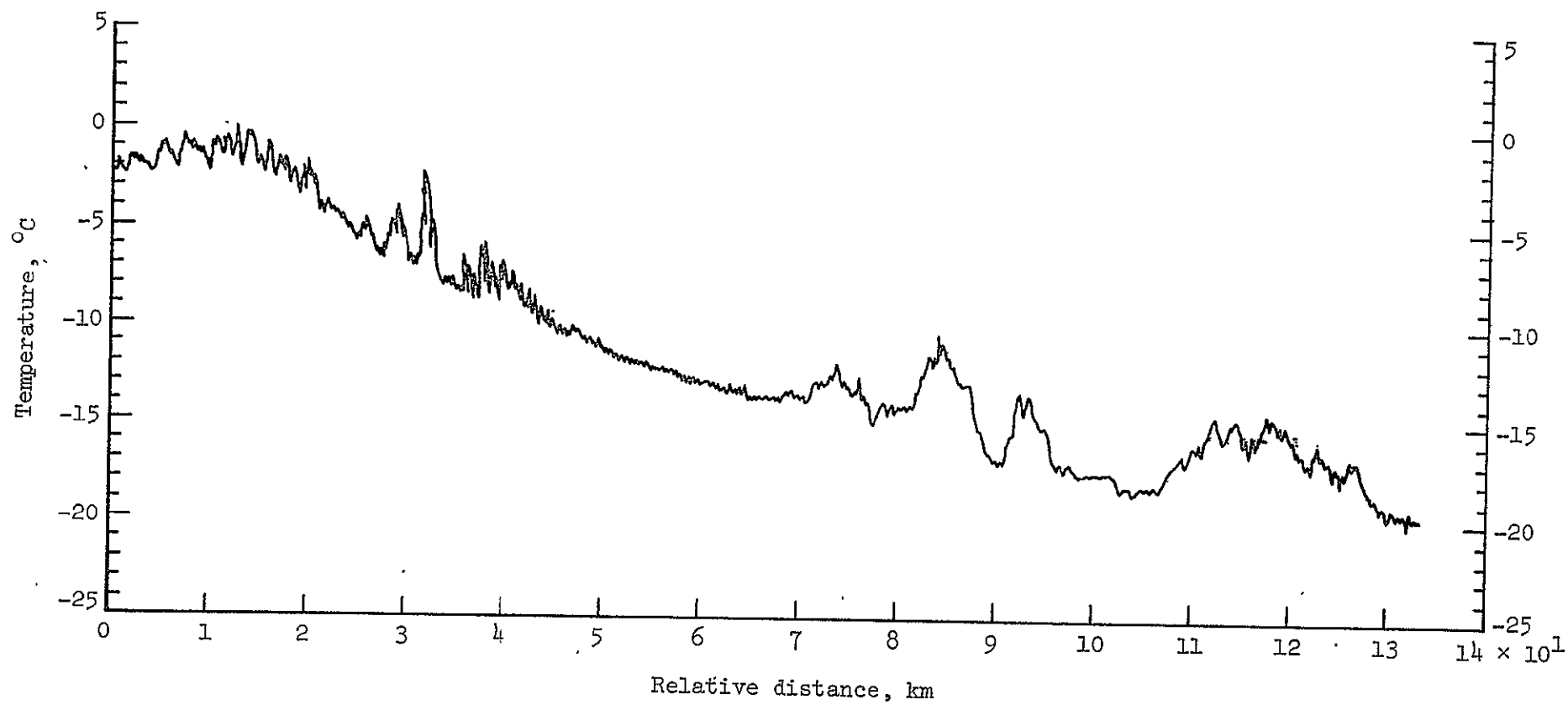


Figure C-72.- Temperature fluctuations observed on run 7, Flight 39 (altitude approximately 4.2 km).

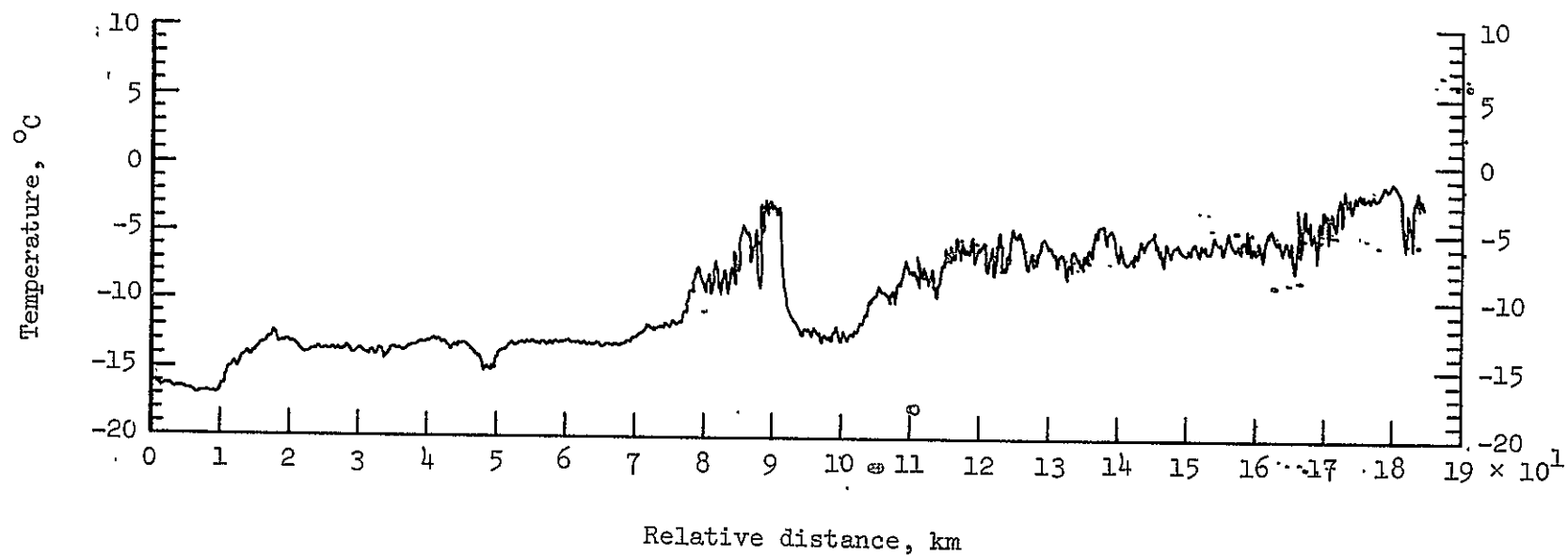


Figure C-73.- Temperature fluctuations observed on run 9, Flight 39 (altitude approximately 4.2 km).

exceeded 31 m sec^{-1} at 2.7 km altitude. Thus, low level turbulence was expected leeward (southeast) of the Tehachapi range. Figure C-74 shows that a relatively deep low (992 mb) was located over southern Nevada with a cold front crossing the coast near Los Angeles. This storm system was moving eastward rapidly and was supported aloft by the deep upper air trough centered over western Nevada (Fig. C-75). Alignment of the surface and upper air winds increased the probability of mountain waves leeward of the Tehachapi range. Both Oakland, CA and Yucca Flats, NV had vertical wind shears of at least $.025 \text{ sec}^{-1}$ from 4.3 to 4.9 km altitude. Several PIREPs of moderate or greater turbulence were received at altitudes up to 4.6 km over California. The NASA F-104 pilot observed eight successive parallel bands of altocumulus clouds leeward of the Tehachapis some two hours before the B-57B takeoff. These clouds, however, lacked a definite lenticular shape, and had all but disappeared by the time the MAT aircraft reached the area. The turbulence leeward of the Tehachapi and San Gabriel ranges occurred concurrently with the passage of an upper frontal zone. Figures C-76 and C-77 show, respectively, the 700 mb temperature field six hours preceding and four hours following the mission. A very large temperature gradient is evident over central and southern California. The Edwards AFB sounding for 1200 GMT shows relatively warm air between 3.0 and 4.6 km (Figure C-78). By takeoff time much colder air had moved in from the north between 2.4 and 4 km, reaching 4.9 km by the end of the flight. Figure C-79 shows data from three aircraft soundings (Runs 2, 4, 8) which indicate that much of the advected cold air reached the sampling area after B-57B takeoff .

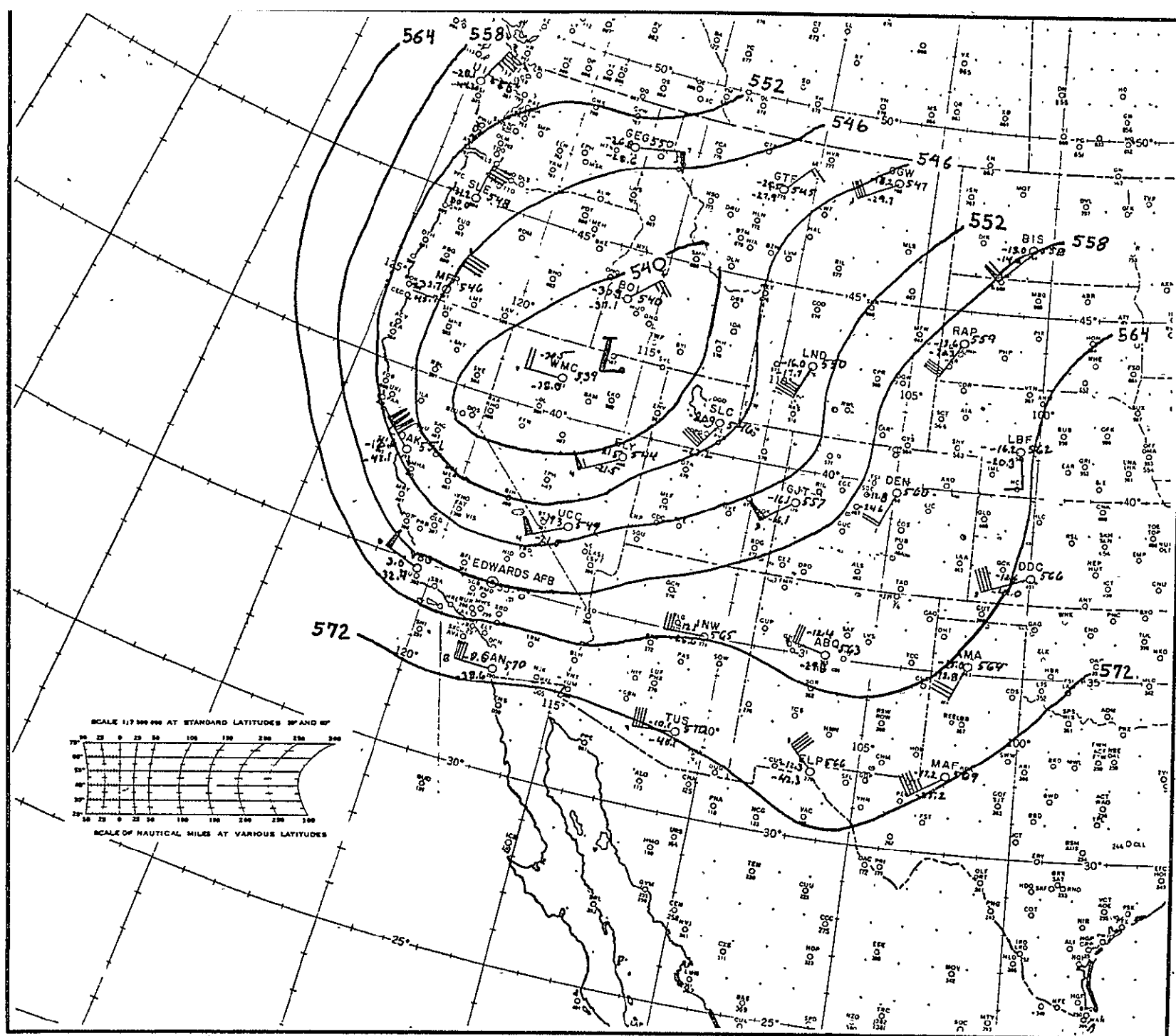
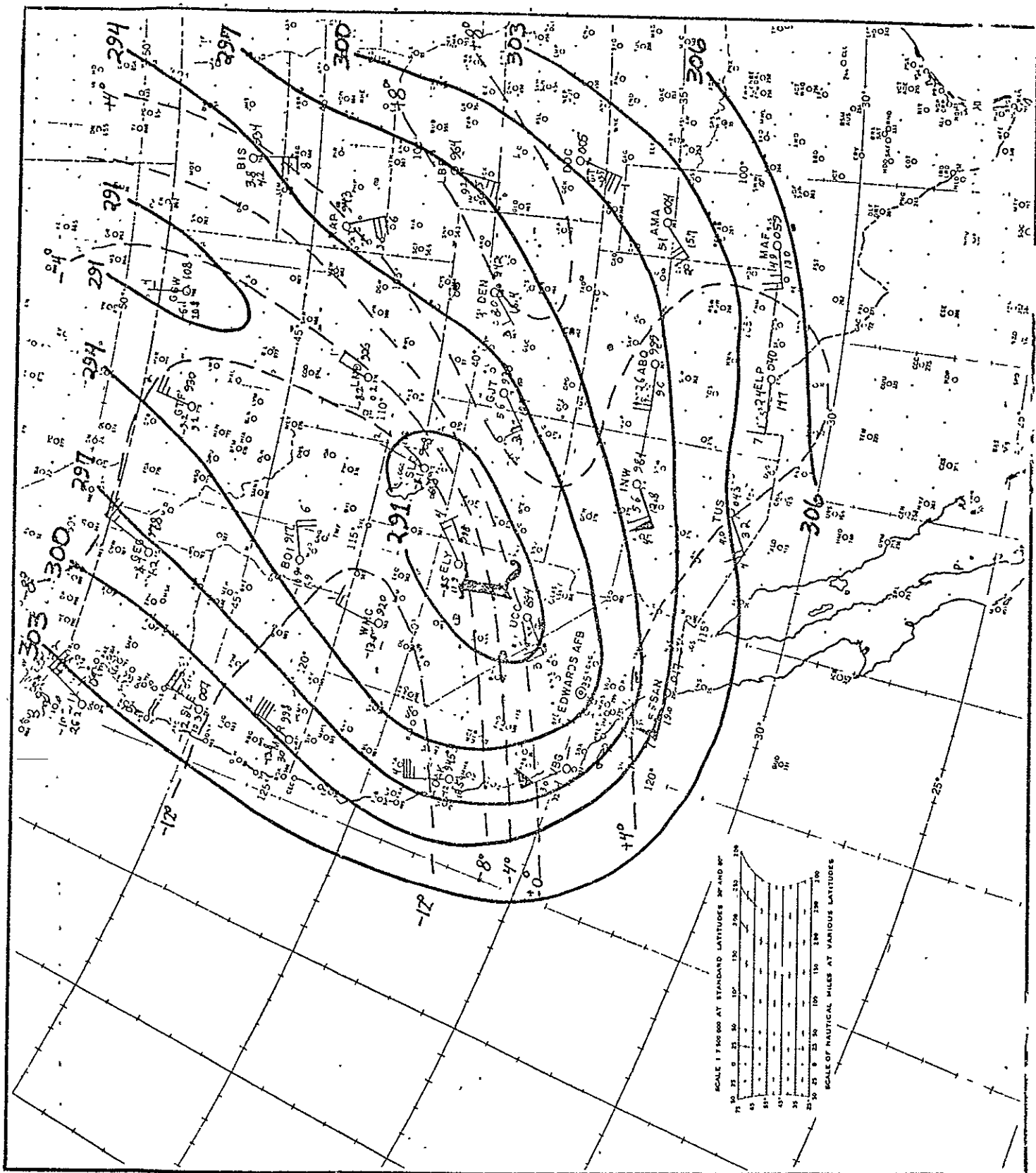


Figure C-75. - 500 mb Analysis, 1200GMT, May 20, 1975. Heights in gpdam.



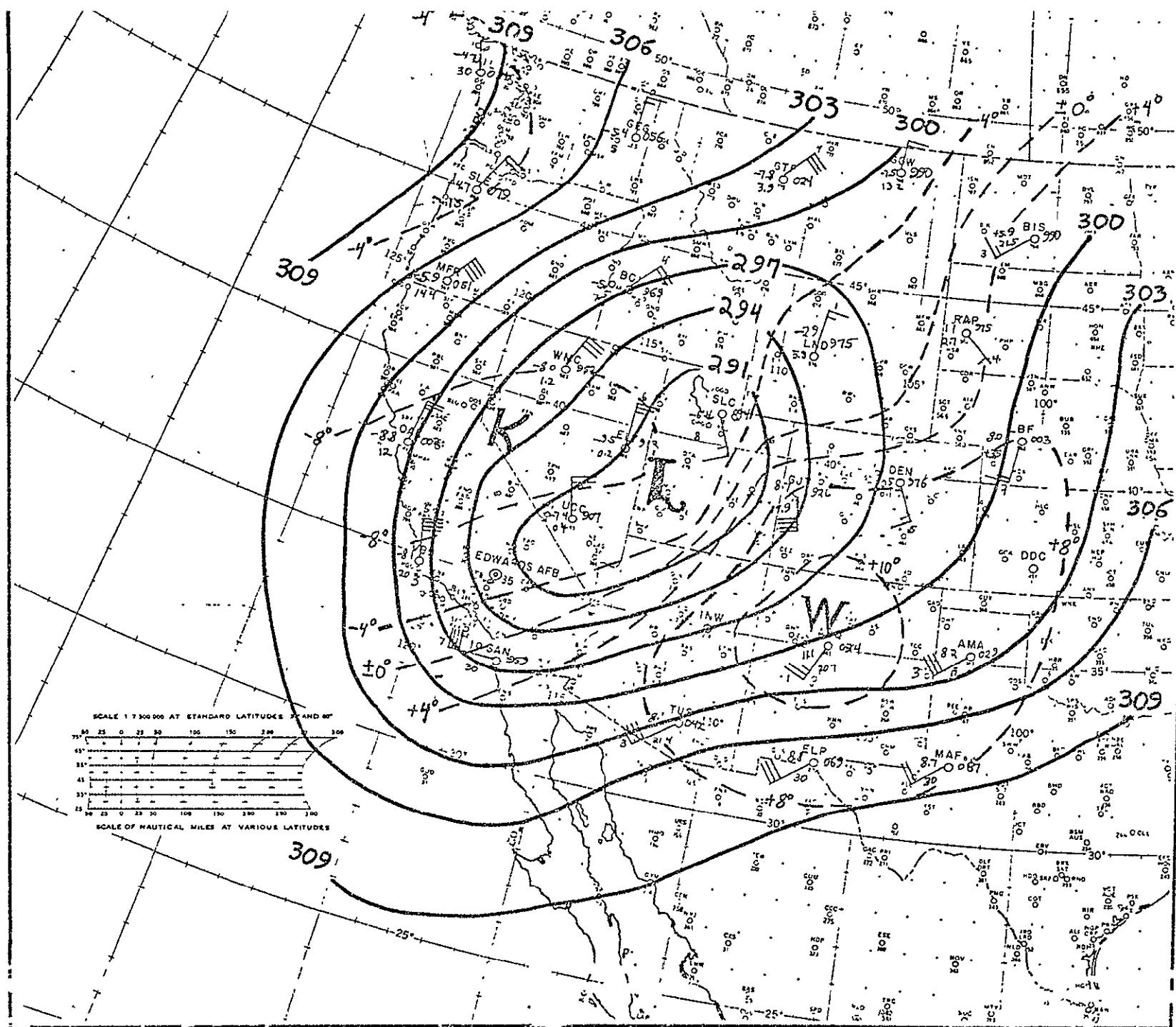


Figure C-77. - 700 mb Analysis, 0000GMT, May 21, 1975. Heights in gpdam.

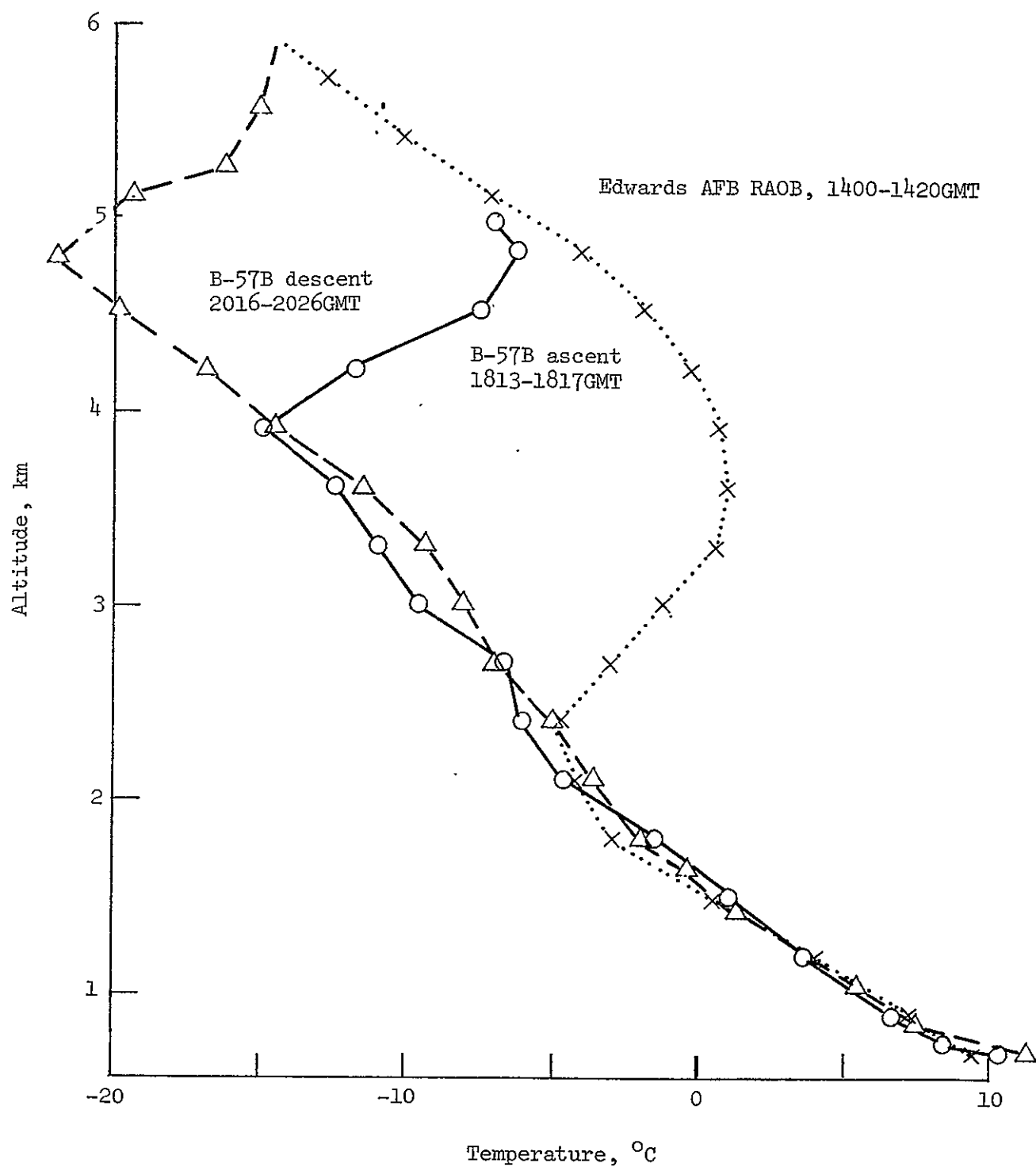


Figure C-78. - MAT B-57B and Edwards AFB, CA, temperature soundings for Flight 39, May 30, 1975.

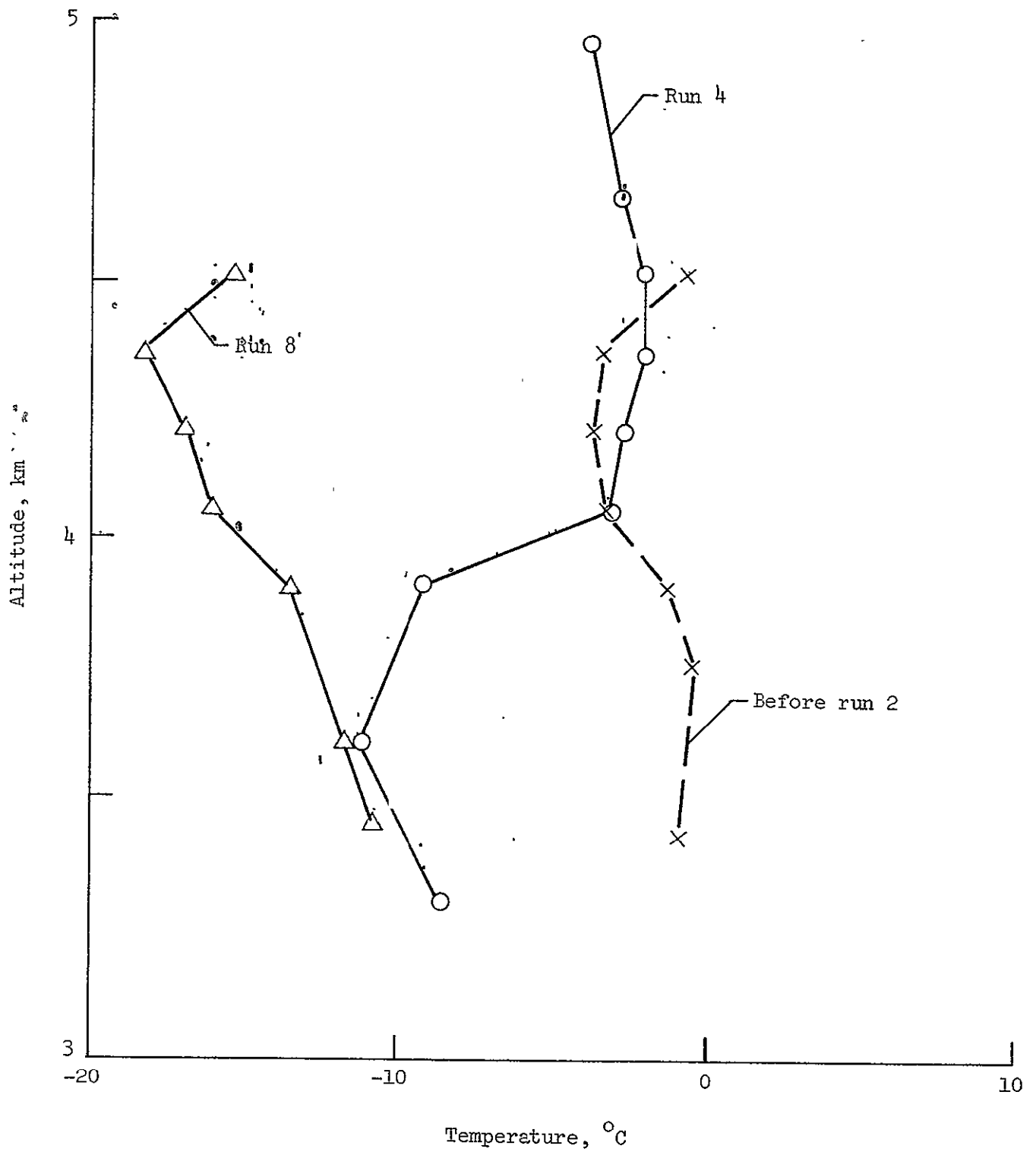


Figure C-79.- MAT B-57B temperature soundings taken in conjunction with Flight 39, May 20, 1975.

Winds calculated from in-flight readings were quite high in the turbulence sampling area, blowing from 270 to 290 degrees between 28 and 38 m sec⁻¹. Wind speed increased from west to east in the sampling area. Surface winds remained quite strong throughout the flight; blowing dust was observed to be suspended at altitudes up to 4.1 km. Cloud cover was mostly scattered, but broken to overcast over the mountains.

Discussion

Moderate and greater turbulence was associated with an intense upper frontal zone traversing a mountainous region. The turbulence was characteristic of breaking waves, being quite variable in intensity and occasionally severe. The most intense turbulence was encountered south of the San Gabriel mountains, where the airflow, which was nearly parallel to the main ridge line, apparently was affected by local peaks and ridges. The strong vertical and horizontal wind shears and very strong horizontal temperature gradients encountered in the turbulent region were associated with the frontal zone.

Flight 40, May 20, 1975, 1649-1853 PDT (2349-0153 GMT)

Flight Summary

Flight 40, the second MAT mission of the day, was scheduled to fly in a negative wind shear region above the jet stream, searching for mountain wave turbulence. The flight area, east and southeast of the Tehachapi range, was the same as that surveyed at lower altitudes on the morning mission (flight 39). Eight hours before the afternoon flight, a NASA T-38 had reported extensive light to light-moderate turbulence in this location at 12 km.

After takeoff the B-57B climbed towards Bakersfield, Calif., to gain the search altitude and then headed southeastward at 12 km to Ontario, CA. During a 7-minute run near Ontario only 3 minutes of very light turbulence was encountered. At this time a commercial pilot report was received of light turbulence northeast of Hector at 12 km. The area was searched but only patchy very light turbulence was found. A run of nearly 17 minutes was made at 12 km on a heading back towards the Tehachapis. Mostly patchy very light and occasional light turbulence was encountered. Light to light-moderate turbulence was noted north of Edwards at 7 km on climbout, 5.9 km on descent, and at 1.2 km and below during both takeoff and landing.

Meteorological Conditions

The synoptic conditions for May 20 have been described from the surface to 500 mb in the resume for flight 39. The surface low located in southern Nevada at 1200 GMT (figure C-74, flight 39) had moved eastward along with the cold front by 0000 GMT, the time of the afternoon flight. Strong gusty winds out of the northwest persisted at Edwards AFB. At 500 mb the cutoff low in northern Nevada (1200 GMT, figure C-75, flight 39) had moved slowly

southeastward by 0000 GMT and jet stream winds appeared to be weakening slightly in the Edwards AFB area as a result. At 0000 GMT negative wind shears above the jet stream were $.029 \text{ sec}^{-1}$ at Oakland but much weaker in the light wind area to the east. Winds remained nearly westerly at upper levels in the flight area. Very little difference in wind speed and direction existed between the region west of Hector, Calif, and that southwest of Palmdale, Calif. Soundings taken during the flight (fig. C-80) show a moderate inversion at the level where the patchy turbulence was found. Temperature fluctuations of 2°C existed on the run west of Hector where temperatures were as much as 11°C warmer than in the Ontario region.

Discussion

The almost total disappearance of significant turbulence above the jet stream in the few hours between the NASA T-38 and B-57B flights suggests that the turbulence may have been associated with a frontal passage during the morning. In-flight wind measurements suggest that the horizontal and vertical wind shears in the search area were weak. The rawinsonde network in the flight area was insufficient to determine whether vertical wind shears weakened appreciably on a synoptic scale in the few hours preceding the flight. A shift in the low level winds towards the north may have been a factor in reducing the influence of the Tehachapi mountains in generating high altitude turbulence.

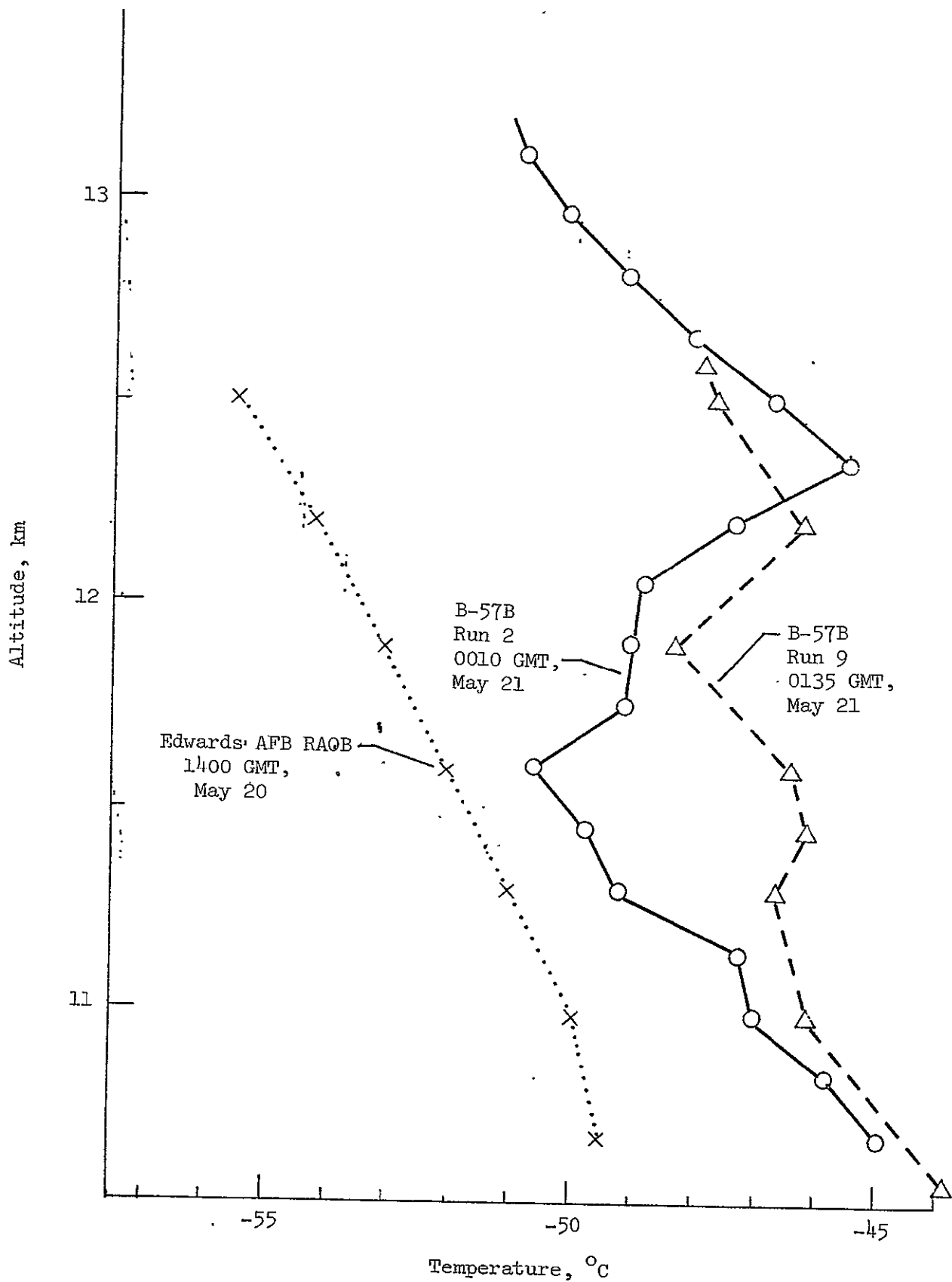


Figure C-80.- Rawinsonde and MAT B-57B temperature soundings for Flight 40, May 20, 1975.

Flight Summary

Moderately large vertical wind shears below 7.6 km and above 11.0 km were noted on the 1200 GMT observations for stations along the California coast. Also, significant horizontal shear due to directional and speed changes existed to the east of the coastal stations. An upper air disturbance associated with the shear zones was expected to move eastward as the day progressed. At 1033 PDT a Boeing 727 reported moderate turbulence 45 km west of Fresno, CA at 7.0 km. This report was followed 1 1/2 hours later by another, received from a Boeing 737 at 6.1 km of moderate turbulence 100 km to the south-southeast of the earlier report. The plan was to search for turbulence in the negative shear region above the jet stream after climbout, then descend to the altitude and area of the two pilot reports.

On climbout (fig. C-81) some light/moderate turbulence was noted below 2.7 km and light turbulence was encountered north of Mojave at 7.4 km. Searching east of the Sierra to 12.8 km produced only brief encounters with very light turbulence at 9.1, 11.0, and 12.0 km. A short patch of light turbulence was again encountered near 7.3 km on the west side of the Sierra while heading into Fresno, with very light turbulence over Fresno at 7.2 km. A record was taken east of Fresno (run 5) at 7.3 km in very light intermittent turbulence. The aircraft then returned to the Edwards AFB area (fig. C-82) where the remaining time was spent searching between 7.3 and 7.6 km for wind shear turbulence. On runs 5, 6, and 7, brief encounters with light turbulence, lasting for approximately 11 km, were recorded. Run 8 produced about 25 km of light and 5 1/2 km of moderate turbulence. 37 km of light to

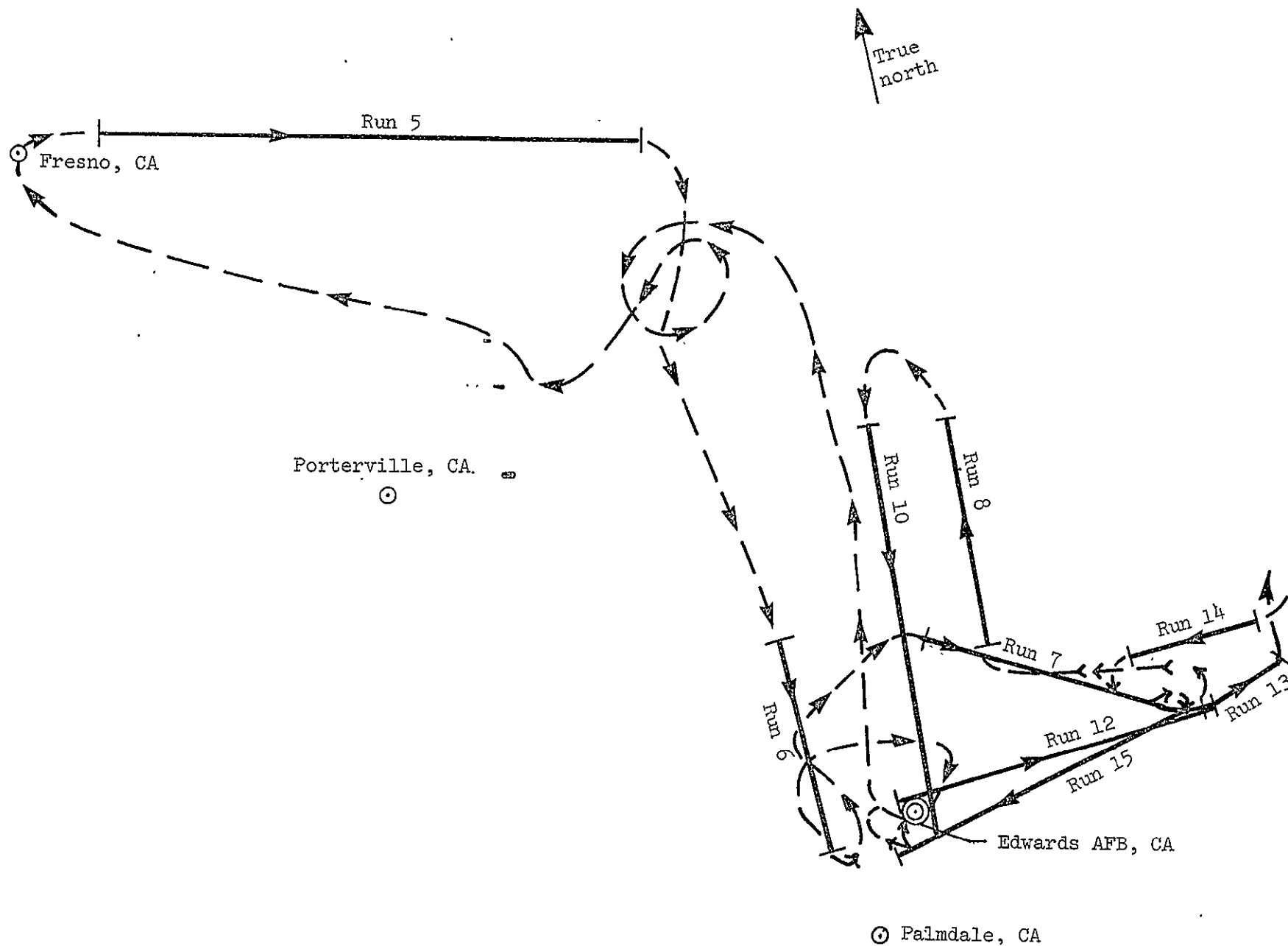


Figure C-81.- Complete track for Flight 41, 2150-0034 GMT, May 20-21, 1975.
All runs at approximately 7.5 km altitude.

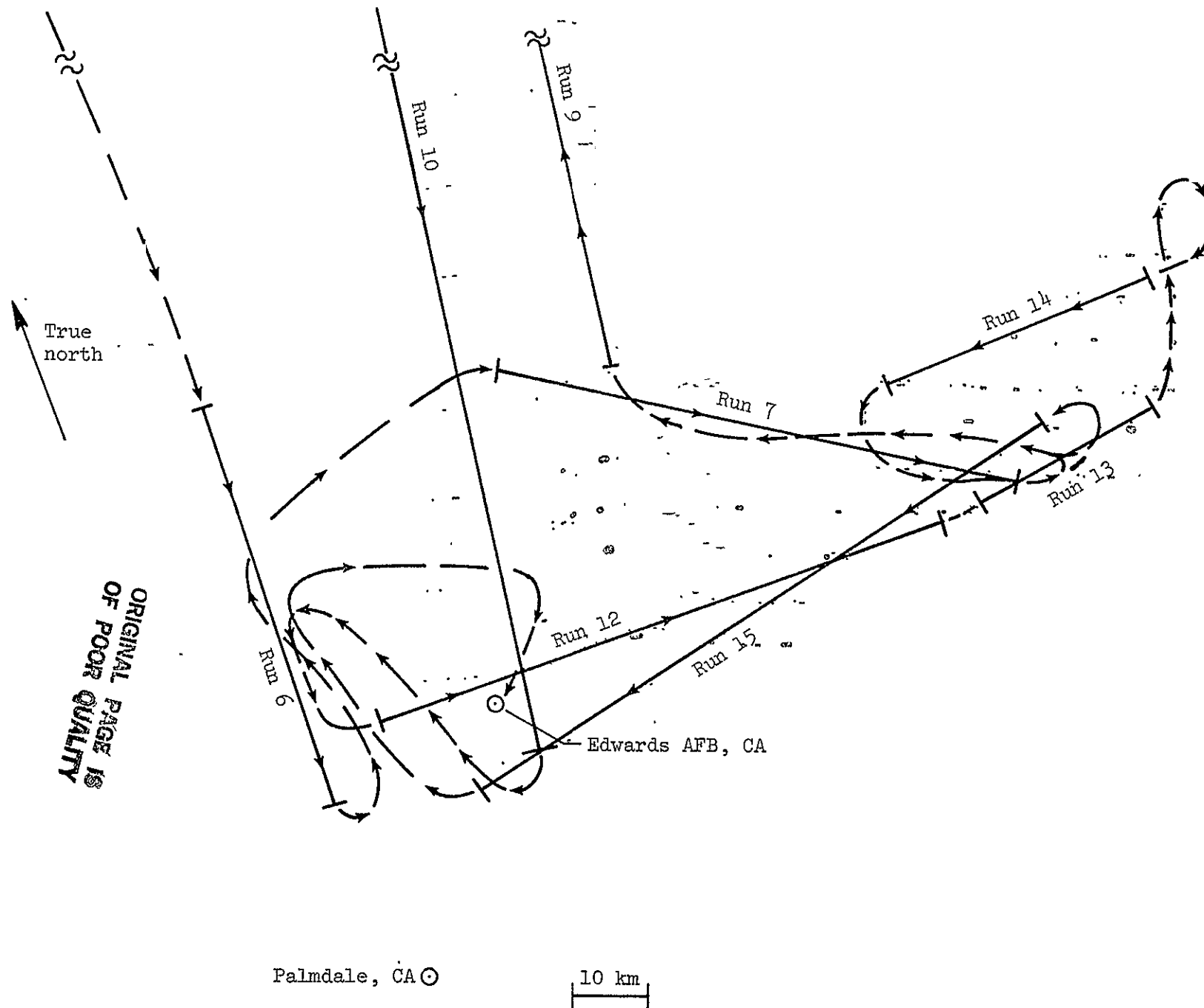


Figure C-82.- Flight track in turbulent area on Flight 41. All runs at approximately 7.5 km altitude.

moderate turbulence occurred on run 10 while the aircraft was heading southward. The B-57B returned to the location of the heaviest bumps on run 10 and headed east-northeastward, encountering 74 km of light-moderate to moderate turbulence. The run was terminated while still in the turbulence because of a restricted zone boundary in the path of the aircraft. Run 13, taken on a slightly different heading, added 18 km of light to moderate turbulence. Two attempts to sample the extended turbulence patch on a reciprocal heading (runs 14 and 15) failed because it was difficult to remain within the narrow light-moderate turbulence zone, estimated on the run 10 crossleg to be only 18 to 28 km in width. Light and occasional light-moderate turbulence was noted on descent below 3.7 km. Many pilot reports from various types of commercial, military, and private aircraft of light to moderate turbulence below 3.7 km were received throughout the day in California.

Meteorological Conditions

(a) Synoptic Situation. A cold front, which had extended through Las Vegas, NV on the previous day, progressed to the eastern border of Arizona by 1200 GMT on the 21st. Surface winds in California were generally from the west, and below 5 m sec^{-1} except for 5 to 10 m sec^{-1} in the deserts and along the Pacific coast. Winds increased during the day due to a tightening pressure gradient west of a low in northern Nevada. 700 mb winds at 1200 GMT were 5 to 10 m sec^{-1} from the north over the Sierra, 10 m sec^{-1} west and south of the Sierra, and up to 18 m sec^{-1} along the southern California coast. A cutoff low at 500 mb centered in Nevada was slowly moving eastward at 1200 GMT. Winds were only 10 to 15 m sec^{-1} in southeastern California and southern Nevada at 500 mb near the center of the low. A tilt in the low axis towards the southwest was associated with sharp

wind direction changes over central and southern California. There were 36 to 41 m sec⁻¹ winds 550 to 740 km from the low center, blowing from the north at Oakland and at points off the southern California coast and from the west at San Diego and points eastward. The 400 mb wind directions were similar to those at lower levels, but speeds were greater, being 13 to 21 m sec⁻¹ near the low and 50 m sec⁻¹ in the jet core to the west and southwest of the center. Only slight increases in wind speeds were noted at altitudes above 400 mb.

The lowest surface pressure in the southwestern U.S. at 0000 GMT on the 22nd was in northern and central Nevada (fig. C-83). The 500 mb axis was now oriented north-south along the Nevada-Utah border (fig. C-84). Winds had decreased on the western side of the low center and increased to the east. Maximum winds at 400 mb to the west of the low appeared to be across the central Sierra and towards the southern California coast (fig. C-85). The altitude of the jet core was slightly higher than on the 1200 GMT observations.

(b) Rawinsonde and Aircraft Data. Soundings from Pacific coast stations showed vertical wind shears of .017 to .034 sec⁻¹ to exist both below and above the jet stream at 1200 GMT. The largest shears were located between 6.1 and 7.6 km and 11.0 to 12.2 km. The zone of maximum shears appears to have progressed eastward along with the movement of the upper level trough, as was evidenced by the shear increase over Yucca Flats, NV between the 1200 GMT and 0000 GMT observations.

Two B-57B soundings taken in the flight area, (runs 9 and 11), showed moderately large vertical wind shears centered near 7.3 km. On sounding

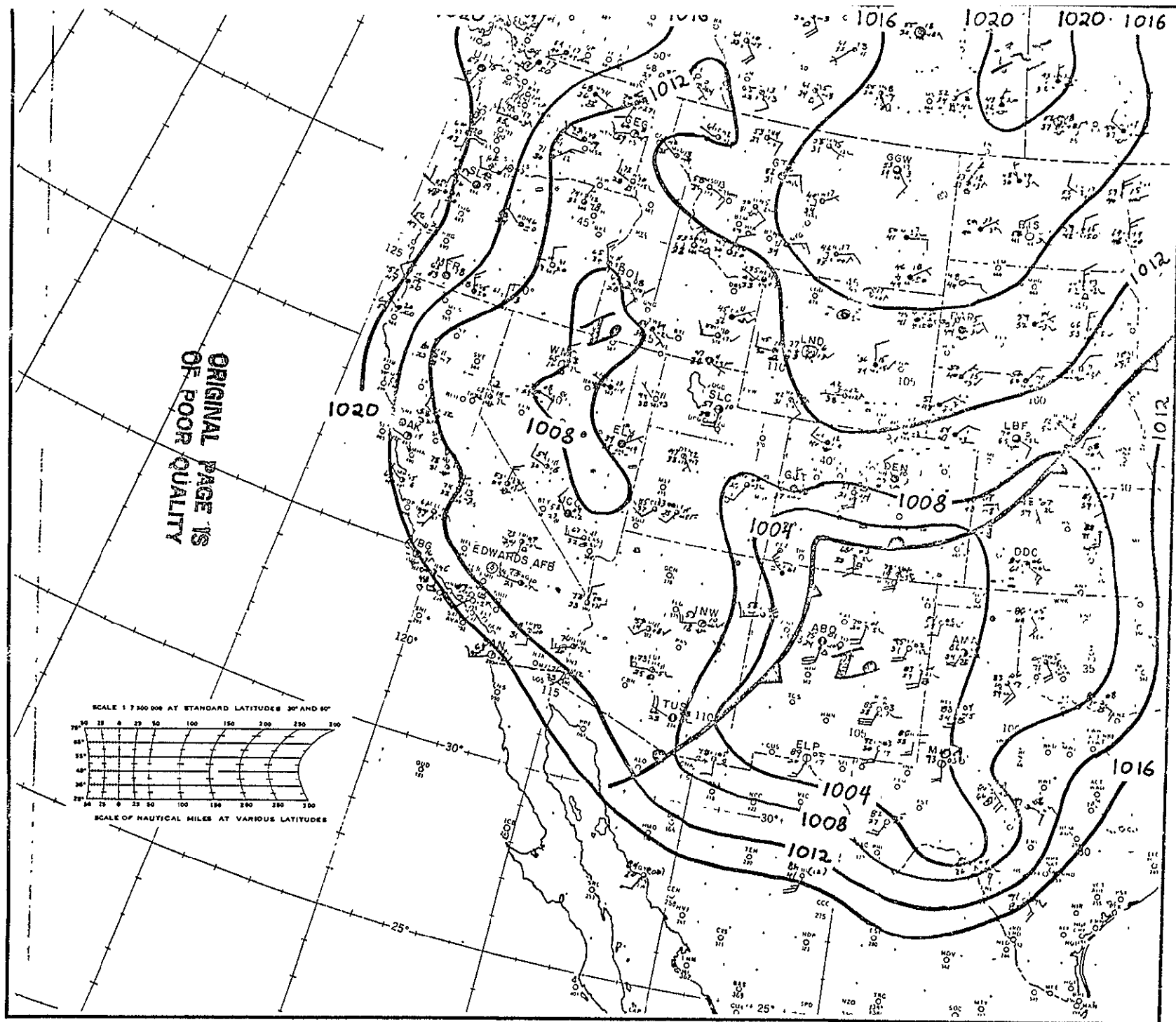
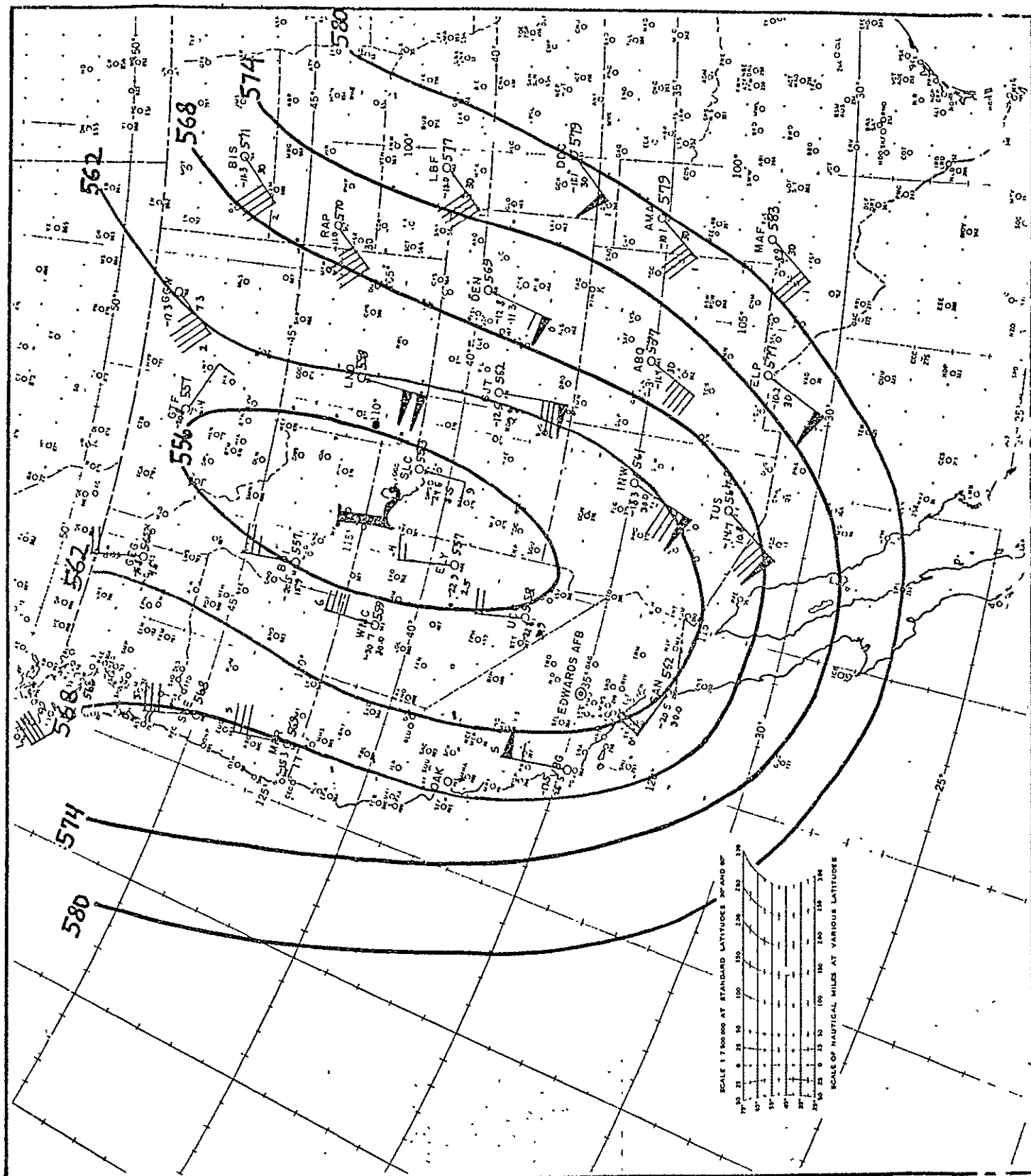


Figure C-83. - Surface Analysis, 0000GMT, May 22, 1975. Pressures in mb.



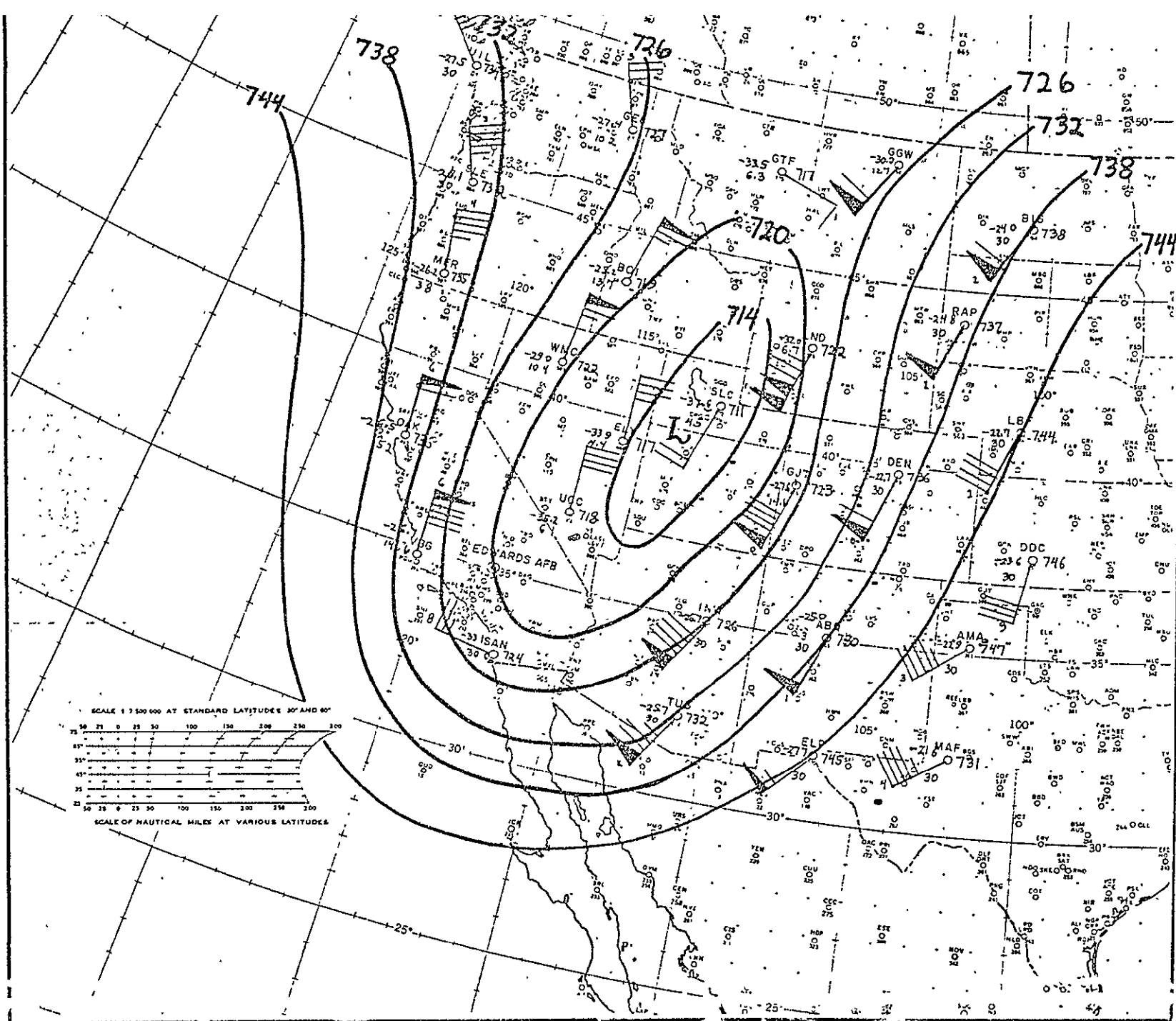


Figure C-85. - 400 mb Analysis, 0000GMT, May 22, 1975. Heights in gpdam.

run 9, taken north of the turbulent area, a shear of $.017 \text{ sec}^{-1}$ and a Ri of .42 were calculated for the 6.7 km to 7.5 km layer. On run 11, the shear increased to $.022 \text{ sec}^{-1}$, lowering Ri to .25 (the critical value) in the area of light-moderate to moderate turbulence near Edwards AFB. Turbulence was encountered during the run through a layer 550 m thick which coincided with the shear layer. The lapse rate for both sounding runs was a uniform -6.9°C/km .

The 0000 GMT RAOBS for Oakland and Yucca Flats show that a horizontal temperature differential as high as 10°C existed across central California at 7.3 km during the flight (fig. C-86). Temperatures obtained in flight suggest that there were some mesoscale features in the flight area that were not apparent in the analysis of synoptically-spaced data. An adjustment to the in-flight temperatures was made for time and altitude differences by comparing aircraft soundings taken at three separate times in the same approximate location (fig. C-87). The resulting temperature field in the area of runs 6 through 15 (fig. C-88) shows a rather sharply defined frontal zone coinciding with the extended line of light-moderate to moderate turbulence. Another area of moderate turbulence to the north appears to have been associated with a warm pocket.

Most of the flight area had scattered to broken cumulus clouds which increased in areal coverage and height over the mountains. Cloud tops were at about 5.2 km in the Sierra region. A cirrostratus cloud layer 600 m thick was noted north of the Mojave desert at 7.3 km on climbout but it moved rapidly out of the area.

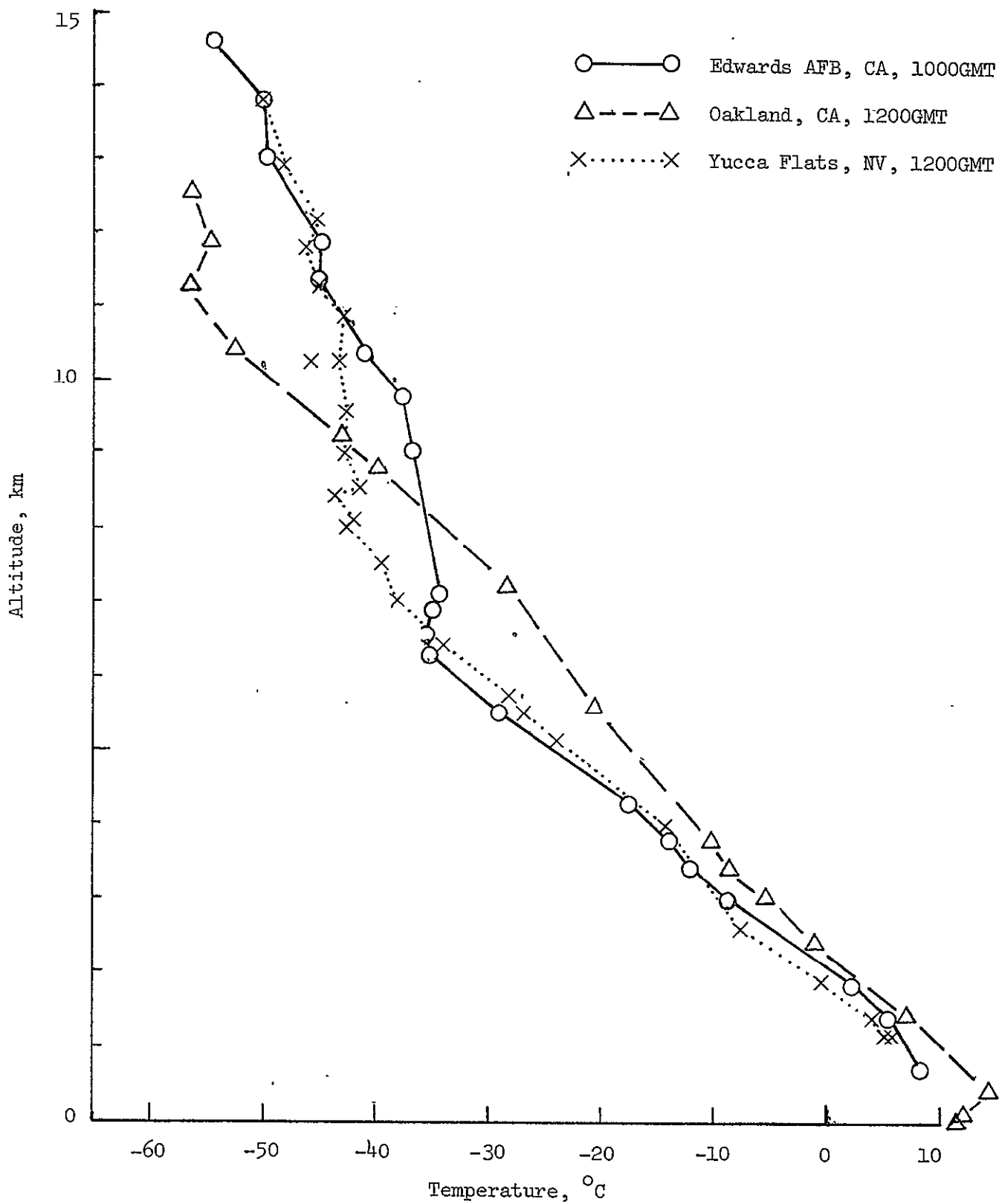


Figure C-86. - Rawinsonde temperature soundings for Edwards AFB, Oakland, CA, and Yucca Flats, NV, on May 21, 1975.

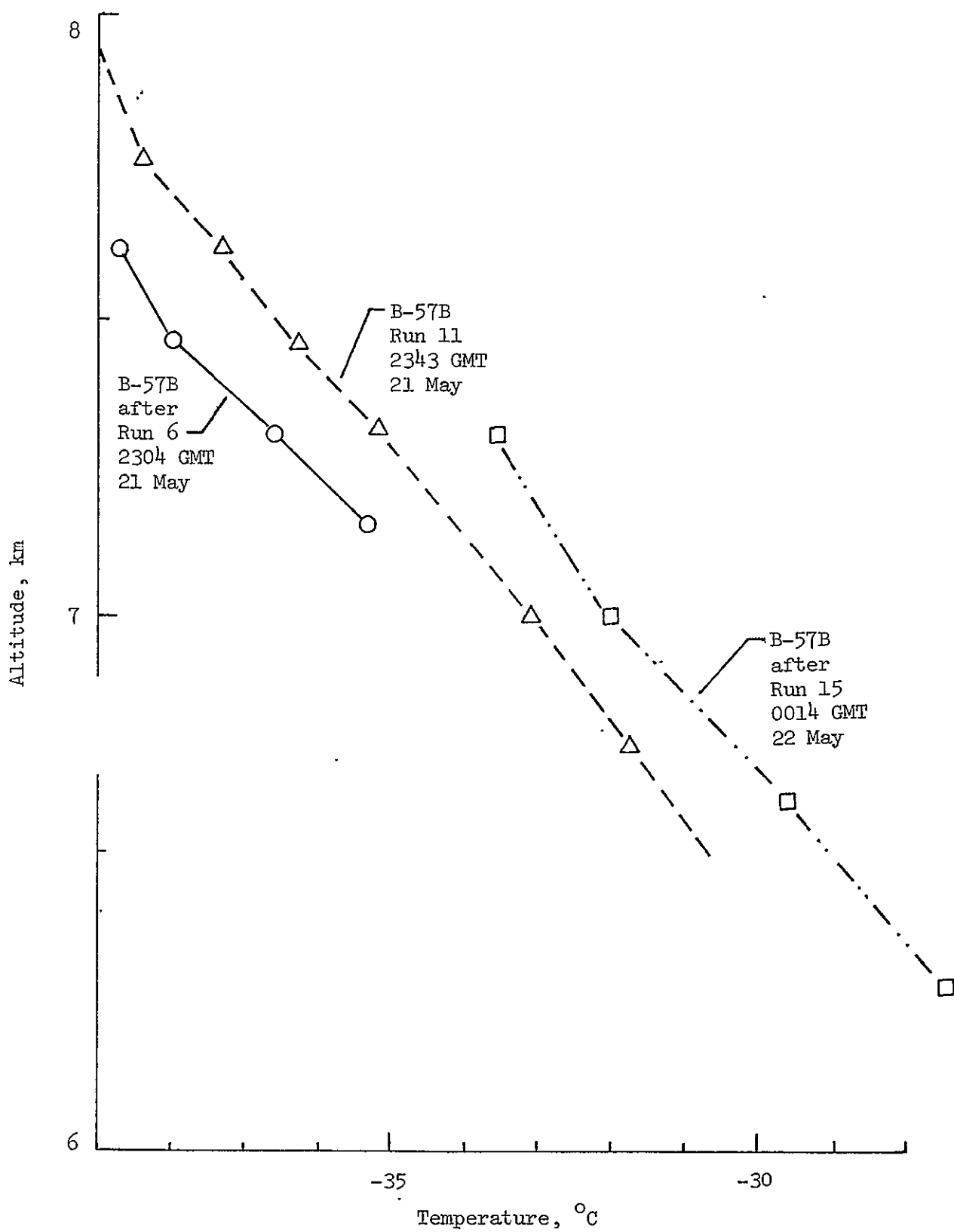


Figure C-87.- MAT B-57B temperature soundings for Flight 41, May 21, 1975.

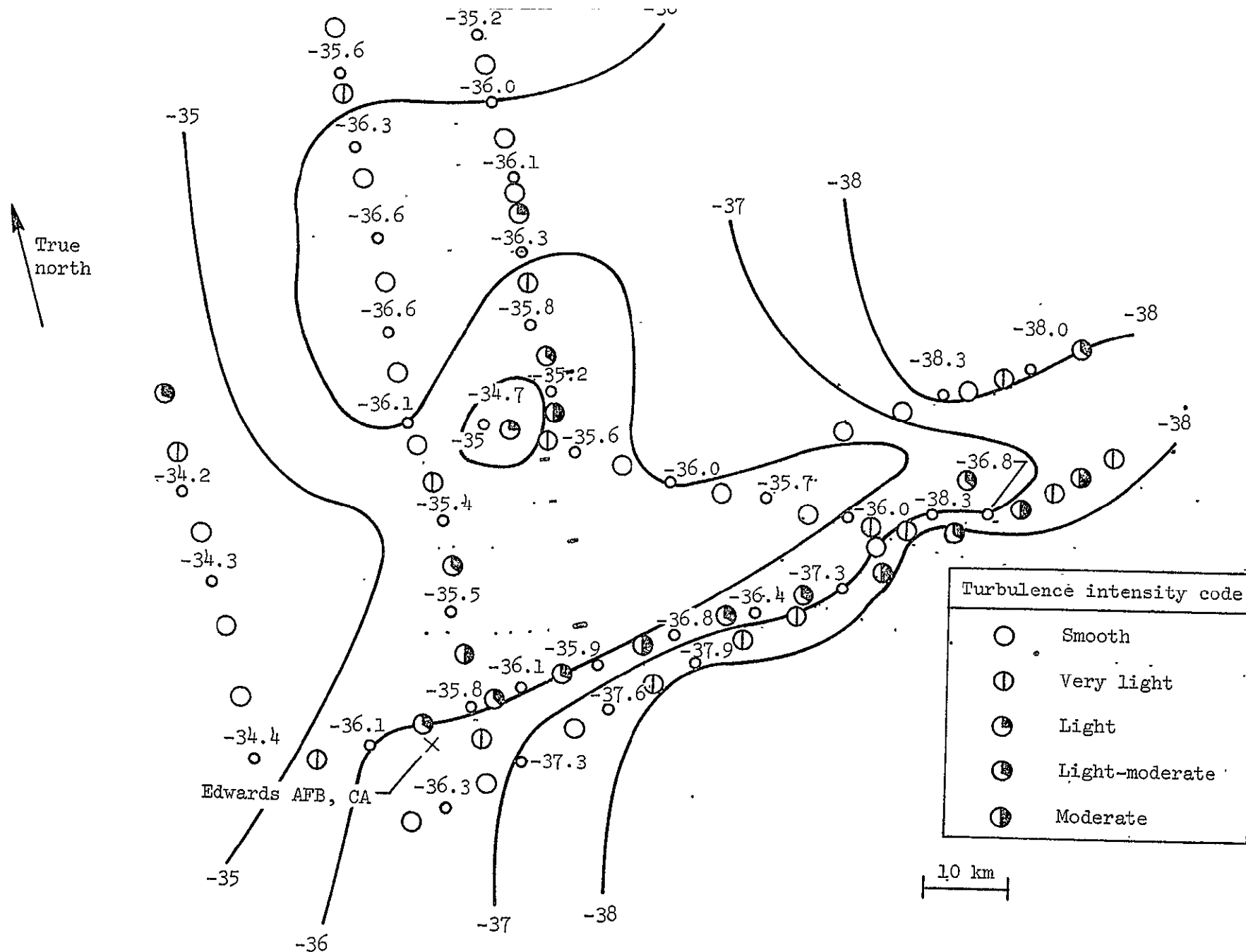


Figure C-88.- Aircraft measured temperature field related to turbulence for Flight 41.
Temperatures in degrees celsius (altitudes 7.3 - 7.6 km).

Discussion

The rather narrow zone of moderate turbulence near 7.3 km appears to have been associated with an upper air disturbance progressing east-southeastward across central California on the 21st. An extensive area of large vertical wind shears existed throughout central and southern California. The shears were probably amplified in a narrow zone southwest of the upper air low, where wind direction changes were prominent and temperature contrasts were sharply defined.

Flight 42, June 13, 1975, 111-1317 PDT (1811-2017 GMT)

Flight Summary

This flight's purpose was to sample turbulence related to thermal updrafts found in mountainous regions and in converging air masses. Forecasts were for temperatures to reach levels well above normal in the desert and inland valley areas of southern California and for thermals to rise to at least 3 km in selected areas. The first location to be searched was the Clark Mountain range which had an elevation of 1200 to 2400 m and was located approximately 75 km southwest of Las Vegas, Nev. (fig. C-89). Three runs (2-4) were made near 4.5 km, two along the main ridge line of the Clark range and one orthogonal to the ridge. On run 2, moderate and occasionally moderate-severe turbulence was encountered for 77 km. Run 3 extended 90 km further than run 2. However, the maximum intensity was slightly less. The crossleg, run 4, started abruptly in moderate turbulence and ended 45 km later, after the turbulence had gradually diminished. The turbulent area was generally marked by building cumulus clouds, the bases of which were approximately 300 m above the sampling altitude. Occasional lulls in the turbulence were experienced, especially in regions with breaks in the clouds.

Run 6, a low altitude run which lasted for 74 km, consisted mainly of moderate and greater turbulence. The run was at 1.6 km, along the shoulder of the Clark Mountains. It was followed by a brief encounter with a dust devil at 1.8 km (run 7) which produced incremental accelerations of +1.0 g and - 0.4 g.

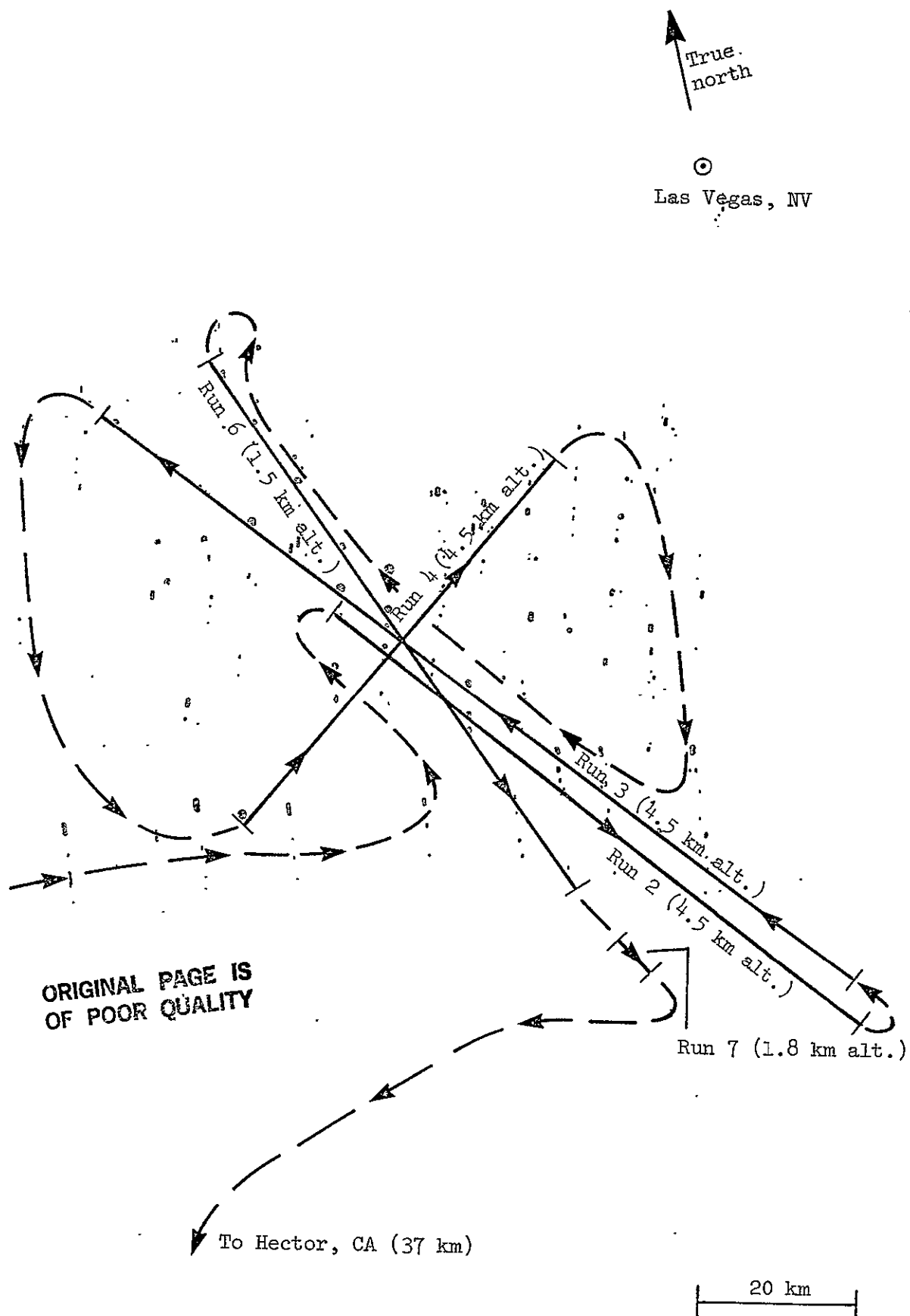


Figure C-89.- Track in thermal turbulence area, Flight 42, June 13, 1975.

Two runs were made in a land-sea breeze convergence zone at 3.3 km, about 75 km east of Edwards AFB (figure C-90). The frontal zone was defined by a dividing line between scattered cumulus clouds on the unstable or land breeze side of the front and the cloud-free area on the stable or sea breeze side. Run 8 was flown across the convergence zone so that turbulence could be sampled in the two distinct air masses. The first part of this 55 km run was in moderate and occasionally moderate-severe turbulence which gradually gave way to light-moderate turbulence in the latter half of the run. Run 9 was along the convergence belt but just within the unstable area. Turbulence lasted for 65 km, initially being moderate-severe but gradually diminishing to lesser intensities and eventually smooth air by the end of the run. It was difficult for the aircraft, which was required to maintain a straight course in order to keep the instrumentation on scale, to stay within the intense turbulence zone, due to the curved nature of the convergence front.

Turbulence was only very light on climbout but occasionally moderate below 3.5 km on descent. In the Clark Mountain region turbulence existed up to 5.3 km.

Meteorological Conditions

Synoptic situation.- On the morning of the 13th a thermal trough at the surface extended from southeastern California to the west side of the Sacramento Valley in northern California. Surface heating was supported aloft by extensive ridging along the western U.S. coastal states. A weak low at 500 mb, centered 370 km southwest of Los Angeles, did not appear to have much effect on the weather in southern California.

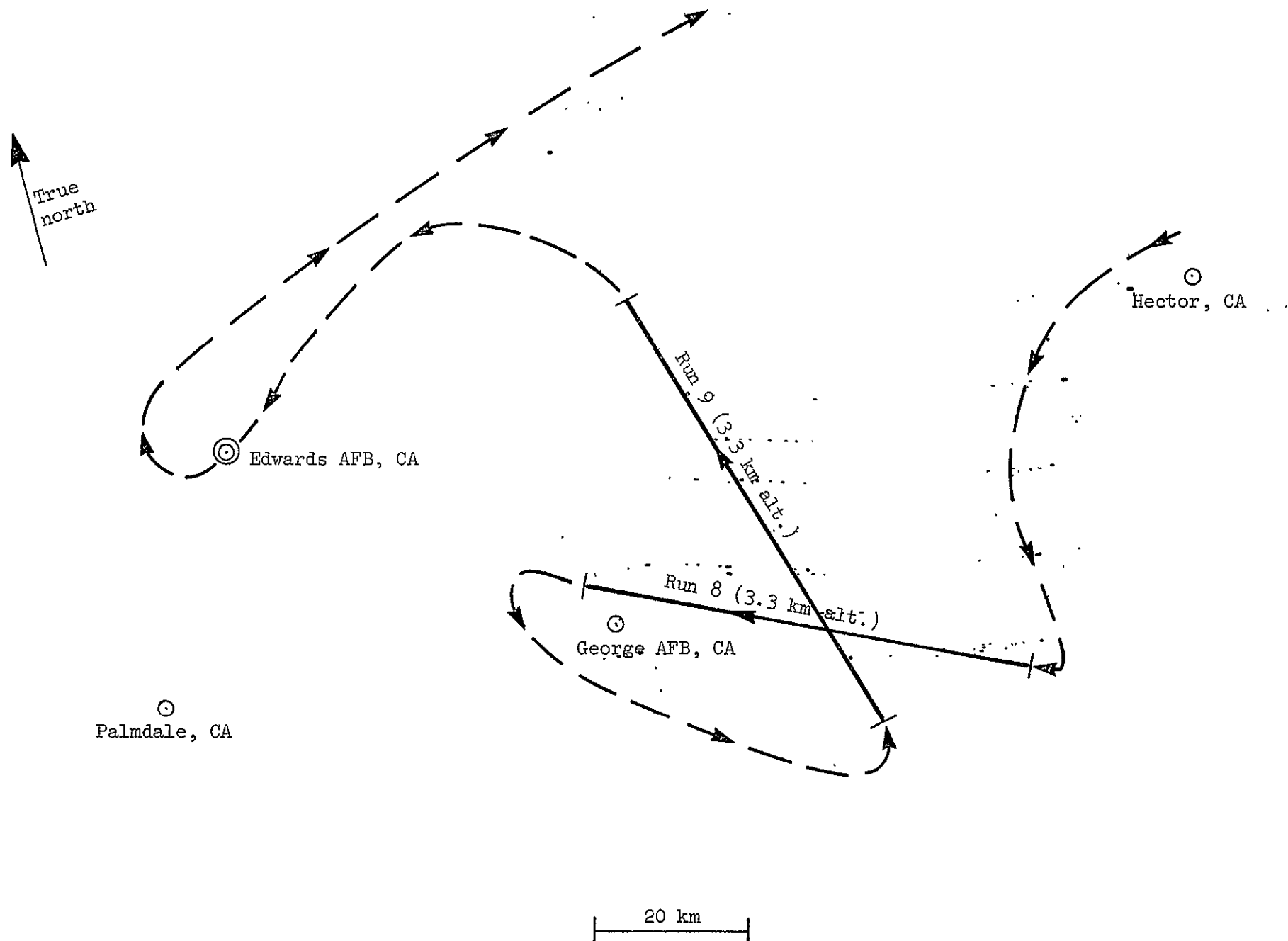


Figure C-90.- Track in land-sea breeze convergence zone, Flight 42, June 13, 1975.

Surface winds were generally light throughout the day in the flight region. Near the convergence zone a dust plume observed in flight 18 km east of George AFB was moving from the southeast at the same time winds from the base were reported as $240^{\circ}/6 \text{ m sec}^{-1}$. Winds aloft were also light, being less than 5 m sec^{-1} at Edwards AFB below 2 km and 5 to 10 m sec^{-1} from 2 to 6 km. Surface temperatures in the low elevations of the flight area were estimated to be around 41°C .

Temperature soundings.- Temperature soundings are plotted in figure C-91 for two altitude excursions of the B-57B, one on climbout and the other near the turbulence zone of the Clark Mountains. Also plotted are the 1300 GMT soundings for Edwards AFB and the 2315 GMT balloon release at Yucca Flats, NV. The early morning sounding at Edwards AFB showed a typical ground inversion with generally unstable conditions from 1.5 to 3 km. Aircraft climbout data showed little change from the Edwards RAOB except for elimination of the ground inversion as the result of diurnal heating. The B-57B sounding in the turbulence area, as well as the Yucca Flats late afternoon balloon release, displayed unstable conditions to at least 4.5 km which partially accounts for the large thermals and moderate-severe turbulence that existed in the flight area.

Discussion

Above normal ground heating resulted in general instability to moderately high altitudes and light to occasionally moderate turbulence throughout the southern California desert regions. Additional instability occurred over the mountains as ground heating produced higher temperatures than found at the same elevation over valleys. Also, converging land and

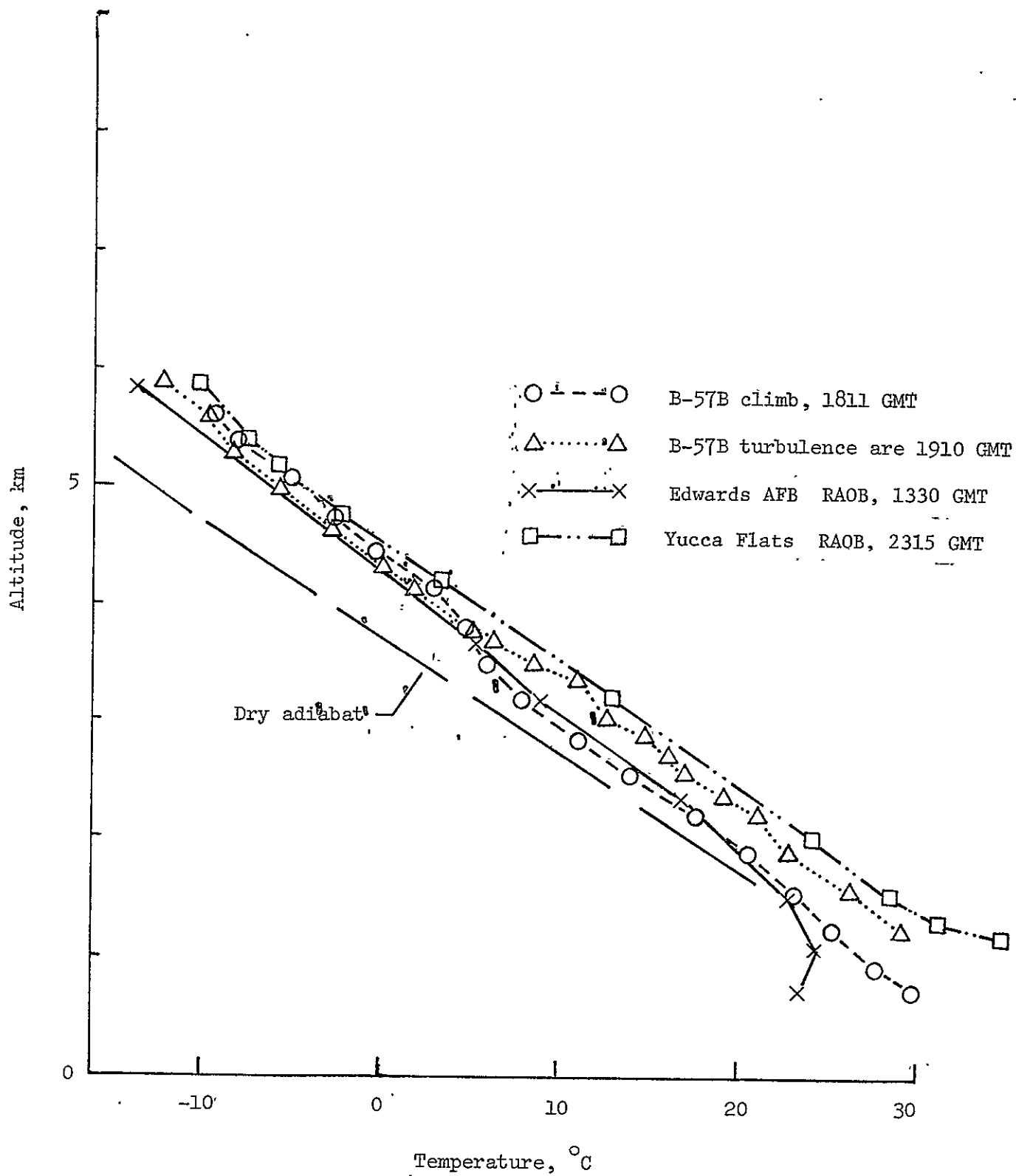


Figure C-91.— MAT B-57-B, Edwards AFB, and Yucca Flats, NV, temperature soundings for Flight 42, June 13, 1975.

sea breezes increased the upward momentum of the thermals in the area 75 to 90 km east of Edwards AFB. The result was two distinct areas of moderate and occasionally moderate-severe turbulence.

Flight 43, June 17, 1975, 1203-1435 PDT (1903-2135 GMT)

Flight Summary

The purpose of the flight was to seek mountain wave turbulence to the lee of the Sierra and the central Nevada ridges. The B-57B flew to the west of the Owens Valley and northeast of Lake Tahoe at 9.1 km, where weak wave activity and occasional very light turbulence were noted near large lenticular clouds. A 10 minute run (run 3) was taken at 8.8 km while heading eastward across a series of north-northeast to south-southwest-oriented ridges in central Nevada. Only about 40 seconds of light turbulence occurred. There were 3 to 4 shallow wave crests on the run and the turbulence appeared to coincide with the trough portion of a wave. A patch of turbulence similar in size and intensity to that of the previous run was encountered on the return to the west during run 4 just north of and 1200 m lower than the turbulence of run 3. After a climb to 10.6 km, two more extended runs were taken, one northeast of Lake Tahoe (run 7) and one across some ridges east and northeast of Lone Pine (run 8). Only occasional very light turbulence and no significant wave activity were found on these runs.

Meteorological Conditions

A storm system that was rather intense for so late in the season had developed in the far west prior to the flight. Surface winds associated with a slow moving front gusted to 26 m sec^{-1} at Edwards AFB on the morning of the flight. Ridge top winds reached 13 to 15 m sec^{-1} and higher out of the west-northwest across the Sierra, with slightly weaker westerly winds

to the east. A cutoff low at 500 mb, centered in northern Oregon at 1200 GMT was forecasted to move eastward in the next 12 hours. The jet stream was located in northern California at 1200 GMT and winds were 33 to 39 m sec⁻¹ in central California. They increased to near 50 m sec⁻¹ in the next 12 hours, however, as the cutoff low moved southeastward. Wind directions remained unchanged. A number of sharply defined large lenticular clouds that were observed close to the flight track, especially at 8.8 km and above, appeared to dissipate during this period. The largest vertical wind shears over the southwest were at Oakland, CA, of .025 sec⁻¹ between 10.7 and 11.0 km, and at Vandenberg AFB, CA, of .022 sec⁻¹ between 7.3 and 8.5 km. Several pilot reports of turbulence were noted in the flight area below 3.7 km but only an occasional one at higher altitudes.

Discussion

The change of wind direction associated with the frontal passage resulted in the wind flow's becoming non-orthogonal to the Sierra ridgeline and a turning of the wind with height above the ridges. The dissipation of lenticular clouds gave visual evidence of a reduction of wave activity during the flight. The only significant turbulence encountered was of short duration and was found well east of the Sierra where the flow appeared to be more orthogonal to the ridges. Although the intensity of the storm system was rather unusual for so late in the season, large temperature and height gradients were absent, as might have been expected in an early summer situation.

CONCLUDING REMARKS

The results of forty-six clear air turbulence-sampling missions performed with the MAT B-57B aircraft have been documented from a meteorological viewpoint. The data have been presented in a manner designed to allow correlation of the turbulence spectra derived from the project with the synoptic and mesoscale conditions associated with the turbulence.

In the program, turbulence samples were obtained under weather conditions including mountain waves, jet streams, upper fronts and troughs, low-level mechanical and thermal turbulence, and turbulence in clear air near thunderstorms. Turbulence was encountered and measured on 20 flights comprising 77 data runs. In all, approximately 4335 km were flown in light, 1416 km in moderate, and 255 km in severe turbulence during the program.

The flight planning, operational and weather forecasting, aspects of the MAT program have been discussed. It was concluded that the practice of engaging the full-time services of a project meteorologist - airborne observer was particularly productive in obtaining a high frequency of turbulence encounters and conserving project resources. Suggestions for improvements to be incorporated in future turbulence forecasting/sampling efforts were also presented.

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16. Abstract <p>The results of 46 clear air turbulence (CAT) probing missions conducted with an extensively instrumented B-57B aircraft are summarized from a meteorological viewpoint in a two-volume technical memorandum. The missions were part of the NASA Langley Research Center's MAT (Measurement of Atmospheric Turbulence) program, which was conducted from the NASA Langley Research Center (on Langley AFB, VA) and the NASA Dryden Flight Research Center (on Edwards AFB, CA) between March 1974, and September 1975, at altitudes ranging up to 15 km.</p> <p>Turbulence samples were obtained under diverse conditions including mountain waves, jet streams, upper level fronts and troughs, and low altitude mechanical and thermal turbulence. CAT was encountered on 20 flights comprising 77 data runs. In all, approximately 4335 km were flown in light turbulence, 1415 km in moderate turbulence, and 255 km in severe turbulence during the program. The first volume presents the flight planning, operations, and turbulence forecasting aspects of that portion of the MAT program conducted with the B-57B aircraft, as well as the overall results and recommendations for future turbulence sampling programs. In the second volume (Appendix C), 27 MAT flights of particular meteorological interest are each described by narrative summaries, supplemented in some cases by synoptic maps and rawinsonde sounding data. This has been done in a manner to facilitate correlation with the turbulence time histories and power spectra derived in the project. Some photographs of clouds are also included, in order to show some of the cloud patterns which may serve as visual warnings of turbulent conditions.</p>					
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